CHAPTER 11

COMPETING TECHNOLOGIES

11.1 SCOPE OF CHAPTER

11.1.1. Technology Comparison

Energy provides essential human needs such as heating and cooling; electricity to our homes, factories, and businesses; propulsion for transportation; and the ability to operate a wide range of portable electronic devices. There are a number of different energy technologies that satisfy such needs, and one of the key questions any new energy technology is not whether it can meet these needs, but whether it can meet them better than existing technologies. How one defines the better technology is open to some debate, but this Chapter will compare various options on the basis of a range of factors including engineering and system aspects, suitability for specific applications, cost, efficiency, and environmental impact. The chapter will focus on the applications that fuel cells are best suited for—electricity generation, distributed and remote power, transportation, and portable power—and on the wide range of energy conversion technologies that will compete with fuel cells in these specific applications. The end of the chapter gives technical and economic comparisons of fuel cells and the competing technologies.

11.1.2. Power Generation and Transportation

Power generation and transportation are two energy sectors that, at the present time, rely almost exclusively on the combustion of fossil fuels in thermal power systems (heat engines). These sectors account for approximately 65% of primary

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energy use in the United States. The steam heat engines have been in operation since the middle of the 18th century, while the first internal combustion engine was developed in the 1860s. Current heat engines achieve efficiencies of the order of 20–40%. The use of fossil fuels leads to a number of problems including regional air pollutants that affect health and air quality and CO_2 emission that contributes to global climate change. Since the world's demand for energy is rising, especially in these sectors, it is vital to investigate the different energy technologies currently deployed, as well as advanced energy technologies. In order to mitigate some of the negative effects of energy use, many have proposed using fuel cell power plants for electricity generation and transportation. An important question for fuel cells is how well they can compete with the conventional and advanced systems, such as high efficiency combined cycle gas turbine power plants, for power generation and advanced spark ignition and diesel engines for transportation. Efficiencies for energy conversion and emission of environmental pollutants are two of the most important criteria in determining the choice of the power plant for such applications.

11.1.3. Environmental Considerations

Energy conversion has a major impact on the environment. There is an increasing understanding of the social costs of power plant emissions, in terms of health and respiratory impacts, heavy metal toxins, acid rain, atmospheric damage, and climate change. Environmental regulations mainly in the form of emission standards are increasingly important constraints on all power plants, especially combustion power plants. The increasing costs of improving the least efficient and most polluting fuels and power plants will open a window of opportunity for cleaner, alternative technologies. Additionally, policies such as taxes on carbon or emissions trading may encourage the use of environmentally friendly technologies.

11.1.4. Portable Power Applications

In the 1950s and 1960s, NASA first used fuel cells, powered by hydrogen and oxygen, to power early space flights and provide potable water for astronauts. This was the first case where fuel cells displaced batteries. Other important applications include power for cellular phones, portable laptop computers, and auxiliary power for a wide range of applications. Portable power applications may require high energy and power densities. These engineering characteristics and the economics are two major considerations when choosing among various battery technologies and fuel cells. In general, considerations of efficiency and emissions are not as crucial, although issues related to the disposal of toxic materials are a concern.

11.2. POWER GENERATION AND COGENERATION

11.2.1. Electricity Generation in a Global Energy Context

Electricity generation is one of the major uses of primary energy in the world. It accounts for approximately 40% of the total energy consumed in the USA; transportation, residential and commercial non-electrical heating, and industrial processes account for the balance of energy consumption. Because of its importance and widespread use, there are great incentives for examining the technologies currently deployed for utility scale electricity generation. Fuel cells are being championed as a higher efficiency and environmentally cleaner means of electricity generation. In order for fuel cells to be competitive with the current technologies as well as advanced fossil fuel, renewable, and nuclear technologies, they must compete on a number of key issues including efficiency, environmental attributes, lifetime, and cost. In order to make an assessment of the potential for fuel cell penetration into this area, the following Sections will deal with current and advanced technologies, and specifically, principles of operation, system efficiency, costs, and environmental impacts.

11.2.2. Fossil-Fuel Based Thermal Power Plants

11.2.2.1. *Operating Principles: Steam Cycle.* Fossil fuel-based steam power plants account for a high percentage of electricity generation in the world, as well as in the USA (50–60%). Including nuclear power plants, steam cycle power plants account for 75% of total electricity generation in the USA. The steam plant is a subset of the vapor power plant. Figure 11.1 shows an idealized version of the vapor-power-cycle plant (Rankine cycle).

The vapor power plant consists of the following key components:

- *Pump*. The energy, W_p, is used to compress the liquid working fluid to high pressure.
- *Boiler*. The heat, Q_{in}, is added from a heat source to the working fluid to vaporize it completely.
- *Turbine.* The vaporized working fluid is expanded (and cooled) back to the condenser pressure and this energy, W_t, is extracted from the working fluid.
- *Condenser.* The heat, Q_{out}, is extracted from the liquid-vapor mixture to return it to the saturated liquid state.
- *Generator*. Converts the mechanical shaft work from the turbine into electrical energy.

In most cases, the working fluid is water. Liquid water is compressed to high pressures and then heated at a constant pressure in the boiler to generate saturated steam. The turbine cools and extracts pressure from the steam, partially condensing

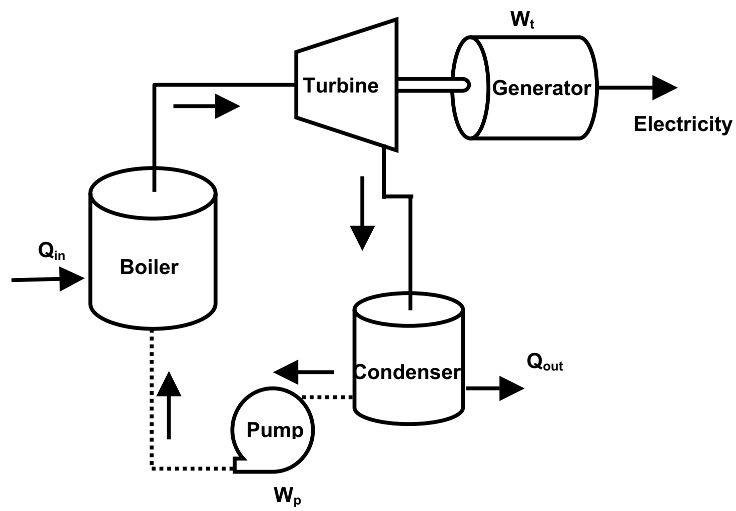

Figure 11.1 Rankine cycle system.

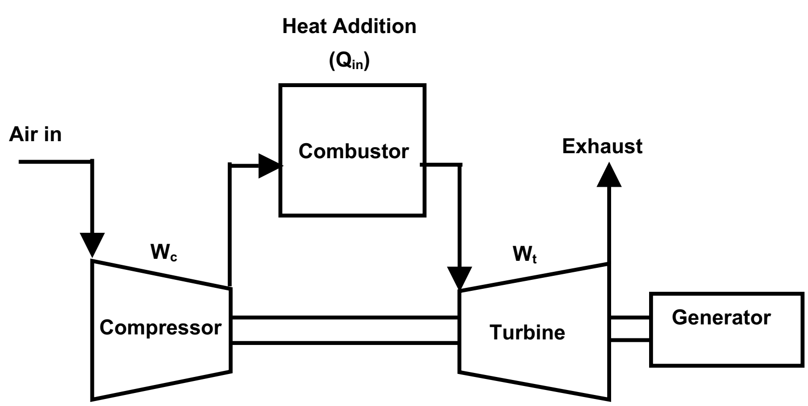

Figure 11.2 Ideal Brayton Cycle system.

the steam to a liquid-vapor mixture (defined by the steam quality), and heat is rejected to the environment as the mixture is condensed completely back to a liquid state.

11.2.2.2. *Operating Principles: Gas Turbine Cycle.* Gas turbines are increasingly popular energy conversion devices and are used extensively in electricity generation, as well as for propulsion in most passenger and military aircraft. Gas turbines account for about 10% of all utility scale power generation in the USA. The simplest gas turbines (Brayton cycle) consist of the following components (Figure 11.2).

- *Compressor*. The energy, W_c, is used to compress inlet air to a high pressure.
- *Combustor.* Heat, Q_{in}, is added to raise the temperature and energy content of air, which is already at a high temperature and pressure.
- *Turbine*. It is used to extract work, W_t, in the form of shaft work and is used to power both the compressor and an electrical generator. The turbine extracts kinetic energy from the high pressure and temperature gas. The air is exhausted to the environment.
- *Generator*. It converts the output shaft work into electricity.

11.2.2.3. *Thermal-Power-Plant Efficiency*. The net work (W_{net}) output from the two heat engines described above is equal to the turbine work (W_t) minus the pump (or compressor) work (W_p):

$$W_{net} = W_t - W_p \tag{11.1}$$

and the efficiency (η_t) is given by:

$$\eta_t = \frac{W_{net}}{Q_{in}} \tag{11.2}$$

where Q_{in} is the heat input.

The maximum amount of work (W_{net}) available (based upon the first law of thermodynamics) is:

$$W_{max} = Q_{in} - Q_{out} \tag{11.3}$$

where Q_{out} is the waste-heat output.

This results in a maximum thermal efficiency (η_{max}), which is expressed by:

$$\eta_{\max} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{T_c}{T_h} \tag{11.4}$$

The final expression in terms of temperatures—the temperature of the heat source (the boiler), T_h, and the temperature of the heat sink (the condenser), T_c, is made on the assumption of reversible heat transfer and represents the maximum (Carnot) efficiency for a heat engine operating between two temperatures. It reveals that the greater the temperature of heat addition (T_h in the boiler) or the lower the temperature of heat rejection (T_c in the condenser), the greater is the efficiency. In a steam plant, the working fluid is water. This ideal cycle can be modified in order to improve overall performance. Superheating the vapor beyond saturation, for example, raises the temperature at which heat is added and increases the efficiency. Reheating is another process that can increase the vapor-power cycle efficiency. Another approach is to utilize several turbines and reheat the working fluid in the boiler between neighboring turbines.

The key action in the steam cycle is the extraction of enthalpy from the high-pressure and high-temperature steam. The turbine inlet consists of nozzles and diaphragms to direct the steam flow into a high-speed jet, driven by the expansion of the steam from the inlet to the exhaust pressure. The turbine blades transfer kinetic energy to the shaft of the turbine. The rotational turbine energy is used to drive an electrical generator. In a gas turbine, the working fluid is a mixture of air, fuel, and combustion products.

11.2.2.4. *Combustion and Environmental Concerns.* Fossil-fuel combustion is the predominant method of energy conversion in the world (~ 85%). One motivation for moving toward renewable energy technologies and fuel cells is the potential for mitigation of the negative environmental and health effects of traditional combustion technologies. Two major environmental concerns associated with fossil fuel combustion are the emission of carbon dioxide and of local air pollutants.

(a) *CO_2 emissions*. Carbon dioxide, CO_2, is a harmful pollutant because of its potentially significant contribution to global warming and disruptive climate change. Anthropogenic CO_2 emission is currently around 22 Gt of CO_2 per year. Such a large flux into the atmosphere disrupts the natural carbon balance and increases the atmospheric concentration—currently about 380 ppm, compared to a pre-industrial concentration of 280 ppm. CO_2, like other greenhouse gases, is an effective absorber in the infrared (especially in the 13–18 μm range) and traps heat in the atmosphere. The Intergovernmental Panel of Climate Change (IPCC) estimates that a doubling of CO_2 concentration over pre-industrial levels could lead to a warming of 2–5 °C by the end of this century. Fossil fuel combustion is the most common source of greenhouse gases (accounting for 98% of CO_2 emissions and 82% of greenhouse gases based upon warming potential). An important strategy in reducing CO_2 emissions is the decarbonization of energy conversion. Figure 11.3 demonstrates the effects of lowering the carbon content (kg-CO_2/kWh generated) of fuels.

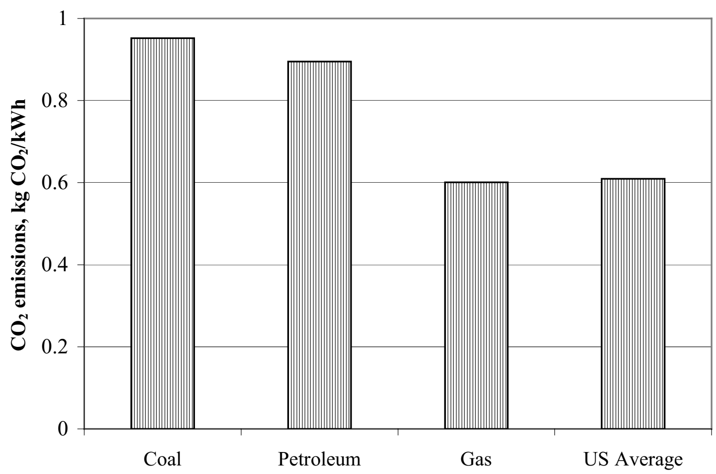

Figure 11.3 Relative carbon intensity of electricity generation.

Even though coal is the major fuel source for electricity generation in the USA, the CO_2 emission level is about 0.6 kg/kWh (similar to that of natural gas), because of the additional use of lower and zero-carbon energy sources (natural gas, nuclear, and hydroelectric). The need to reduce carbon-emission is beginning to be recognized and could affect the usage of high carbon fuels such as coal and petroleum. Another means for reducing CO_2 emissions besides changing carbon intensity is to reduce the energy intensity, i.e., the amount of energy it takes to produce a given unit of GDP. Electric utility power generation accounts for 41% of total USA CO_2 emissions (2.2 Gt CO_2/y for electricity generation out of a total release of 5.4 Gt CO_2/y).

(b) *Local and regional air pollutants*. Combustion of fossil fuels produces other pollutants that can lead to environmental problems such as respiratory disease, urban air pollution, and acidification of lakes and rivers. These effects are more localized than the problem of carbon emissions. Oxides of nitrogen (NO_x) are commonly released when burning fossil fuels because the high flame temperatures oxidize nitrogen from the atmosphere. NO_x leads to ozone pollution and photochemical smog. Sulfur dioxide (SO_2) is another fairly common pollutant that is released during energy conversion. It is not as ubiquitous as NO_x because sulfur needs to be present in the fuel to produce SO_2. Sulfur is present in coal (the commonly used fuel) and also in diesel fuel. SO_2 reacts with

water in the atmosphere to produce acid rain, which can be devastating to biological systems (forests and lakes). It can also form sulfate aerosols, which affect visibility. Other pollutants will be dealt with in more detail when connected to specific energy conversion technologies.

11.2.3. Coal-Based Steam Power Cycles

11.2.3.1. *Operating Principles: System Configurations.* The previous Section summarizes the major operating characteristics of fossil fuel based steam power plants. The most common type of steam power plant in the USA uses coal or other solid fuel (~ 70%). The main differences among the several types of steam power plants are due to the type of fuel and equipment used to convert the chemical energy of fuel to heat energy for boiling water. Coal combustion is accomplished by several methods. First, the solid coal is crushed to form small particles. In pulverized coal burners, the coal is ground into particles about 40 μm in size. This powder is entrained by a stream of air into the combustion chamber. The powder is ignited and the combustion reaction is sustained by volatilization of the coal and subsequent burning. In the boiler, steam is created by pumping water through tubes that are heated mostly by radiation from burning particles. Current steam generators can achieve steam pressures and temperatures up to 300 atm and 600 °C. Another method for coal or other solid fuel combustion is in fluidized beds. The solid fuel and a bed material contained in a vessel are fluidized when air flows upward at sufficient velocity. Combustion temperatures in fluidized beds are significantly lower than those in conventional boilers.

11.2.3.2. *Thermal Efficiency Considerations.* The efficiency of a steam cycle deviates from the Carnot efficiency and the ideal Rankine cycle efficiency because of turbine and pump inefficiencies and heat and pressure losses. Variations on the simple Rankine cycle can improve thermal efficiency. Reheating will split the turbine expansion into two phases with reheating between the two turbines to raise the average temperature. Some steam from the turbine is used to preheat water entering the steam generator. These modifications are found in modern steam plants to increase efficiency and ensure high turbine steam quality. The average efficiency of pulverized coal power plants is approximately 34%, while modern plants capable of achieving higher steam pressures and temperatures can reach efficiencies of 40–43%.

11.2.3.3. *Emissions and Control.* Traditional coal-fired power plants produce a significant amount of pollution. Coal is the dirtiest and most carbon intensive of all common fuels. As discussed in Section 11.2.2.4., some of the most important pollutants are CO_2, SO_2, and NO_x. Coal has the highest carbon content per unit energy of all fossil fuels and is one of the most significant sources for anthropogenic greenhouse gas emissions. Beyond its potential contribution to significant climate change, coal has much more acutely harmful pollutants with

well-documented and quantified impacts—i.e., SO_2 and particulates. SO_2 has a high solubility and is easily absorbed by the human respiratory tract, leading to constriction of airways and worsening of asthma symptoms at relatively low concentrations. The effects of fine sulfate aerosols and other particulates are strongly dependent on particle size; they also lead to respiratory problems and increased mortality. NO_x emissions also contribute to tropospheric ozone formation and can increase respiratory problems.

The main benefits of fluidized bed-combustion-steam generators are that both NO_x and SO_2 raw emissions are significantly lower, reducing the requirements for post-combustion exhaust cleanup. Limestone ($CaCO_3$), added to the fluidized bed, reacts with sulfur to form particulate $CaSO_4$, which can then be removed by particulate filters. NO_x emission is reduced by lower combustion temperatures.

11.2.3.4. *System Considerations.* The focus of this Section is on coal-fed steam plants, but steam generators can also operate on oil and gas. Nuclear power-steam plants are discussed in Section 11.2.5. The average sized steam plant in the USA generates 300 MW of electricity, with a range from 50 to over 1100 MW. Small turbines are found in combined cycle applications where a steam cycle is used as a bottoming cycle for lower temperature heat. Another coal-based power generation system is the integrated gasifier combined cycle (IGCC) system. This system has significantly reduced emissions and has high efficiencies for energy conversion. In this system, solid coal is converted into a clean gaseous fuel, a syngas composed mainly of CO and H_2. The gasifier breaks down the coal and partially oxidizes it in air or pure O_2. The sulfur and other impurities can be removed from the gas stream before combustion. The syngas is combusted to power a gas turbine cycle, which is then followed by a heat recovery steam generator (HRSG) that drives a steam cycle. Details of the gas turbine-combined cycle system are presented in the next Section. The IGCC system can achieve efficiencies around 45%, and projections of efficiencies for advanced systems are over 50%.

11.2.4. Natural-Gas Turbine Power Systems

11.2.4.1. *General Comments on Gas Turbine Systems.* The basics of the Brayton cycle were described in Section 11.2.2.2. According to the US Department of Energy, natural gas turbines are expected to make up more than 80% of the new power generating capacity in the US over the next decade. Major reasons for this shift from traditional steam plants to gas turbine plants are the availability of natural gas, low installed capital cost, high efficiency, fast start-up, and good load following characteristics.

11.2.4.2. *System Configurations for Turbine Systems.* Gas turbines are frequently found in both simple and combined cycle configurations. The simple cycle does not use the rejected exhaust heat from the turbine. These systems are inexpensive, simple to install, and typically used for reserve or peak power

requirements (usually less that 2000 hr/yr operation). Combined cycle systems use the high-temperature exhaust heat of the gas turbine to drive a heat recovery steam generator (HRSG), which is the boiler in a steam cycle. The coupling of these two power cycles increases plant efficiency. These systems are more complex to design and install and are typically used for baseload (continuous operation) power. Gas turbine sizes range from less than 1 MW up to about 300 MW.

11.2.4.3. *Efficiency Considerations.* As described in Section 11.2.2.3, the Carnot efficiency of a heat engine is determined by the ratio of inlet and exhaust temperatures. In a gas turbine, these temperatures are related to the pressures before and after the turbine. Defining a compressor ratio, r_c, as the ratio of pressures that the compressor and turbine operate between, the isentropic efficiency of the simple Brayton cycle is given by:

$$\eta_{\max} = 1 - \frac{T_c}{T_h} = 1 - \frac{1}{r_c^{(\gamma-1)/\gamma}} \tag{11.5}$$

where γ is the ratio of specific heats (C_p/C_v) for the working gas (air).

In a real situation with non-isentropic compressor and turbine efficiencies, the thermal efficiency will not increase indefinitely; instead, it reaches a maximum and then declines with further increases in the compressor ratio. The theoretical efficiency will also increase with the turbine inlet temperature. However, this temperature cannot increase indefinitely because of temperature limitations of the turbine materials. Research on advanced turbine materials and blade cooling raise prospects of working at higher temperatures and achieving higher efficiency.

Operation of a gas turbine with some modifications can increase cycle efficiency or power output. These include:

- reducing compressor work: cooling the inlet gas or having several compressor stages and cooling in between results in a denser, more easily compressed gas and a higher mass flow;
- recycling waste-heat: recuperating the turbines preheat-compressed gas to the combustor via a counterflow heat-exchanger coupled to the exhaust gases;
- increasing average temperature: including multiple turbines and reheating between turbines can increase the average temperature without increasing the turbine inlet temperature; and
- increasing mass-flow: injecting steam can lower combustion temperatures and increase the mass flow for an increased power output.

These cycle variations can be combined into various configurations depending upon the specific application and economics involved with each individual plant. A simple gas turbine cycle exhausts at high temperature, thereby wasting useful heat

and limiting efficiency to around 27–30%. Utilizing this heat to drive the bottoming steam cycle in a combined cycle system can increase efficiencies to above 50%.

11.2.4.4. *Emissions and Control.* The primary pollutant from natural gas-fired turbine power plants is NO_x. Since most natural-gas resources are low in nitrogen content, this NO_x formation occurs in the high temperature reaction between oxygen atoms and atmospheric nitrogen in the combustion zone. Since NO_x formation is strongly temperature-dependent, the primary control for NO_x formation is achieved by reducing temperatures by steam or water injection, lean combustion operation, or multi-stage combustors. Selective catalytic reduction (SCR) is used to lower post-combustion NO_x emissions by combining vaporized ammonia to the exhaust gases and passing over a catalyst bed. Other pollutants such as carbon monoxide (CO) and other incomplete combustion products can be catalytically oxidized. SO_2 emissions are generally low because natural gas does not contain much sulfur. As shown in Figure 11.3, natural gas, which is mainly methane (CH_4), has a lower carbon content per unit heat energy than coal, thus yielding a lower CO_2 emission than electricity derived from coal. However, pipeline and other natural gas leaks can have significant effects on atmospheric radiative forcing since methane is a very powerful greenhouse gas with a higher global warming potential than CO_2 (~21x stronger than CO_2). Methane can also be involved in the formation of ozone and photochemical smog.

11.2.4.5. *Economic and System Considerations.* Overall annual electricity cost will depend on capital equipment cost, fuel costs, operations and maintenance costs, and the number of hours of operation. Given the higher fuel costs of natural gas vs. coal and the higher capital cost of steam cycles vs. gas turbines, natural gas turbines will be more economical for load following while steam power systems will be more economical for baseload power systems. Due to combined cycle plants having higher capital costs, but increased efficiencies (and thus lower fuel costs), the same result applies. In addition, natural gas is subject to greater fluctuations in price than other fuels.

11.2.5. Nuclear Based Thermal Power Plants

11.2.5.1. *General Comments on Nuclear-Power Systems.* Nuclear power was once touted as a future source of limitless and near-zero cost of electricity. Problems with long reactor construction times, budget overruns, higher operating costs, public perceptions of safety, and nuclear waste storage have retarded nuclear power development. Even so, nuclear power accounts for close to 20% of electricity generation capacity worldwide and nuclear power is gaining renewed attention as a reliable and well-established technology for providing CO_2-free electricity.

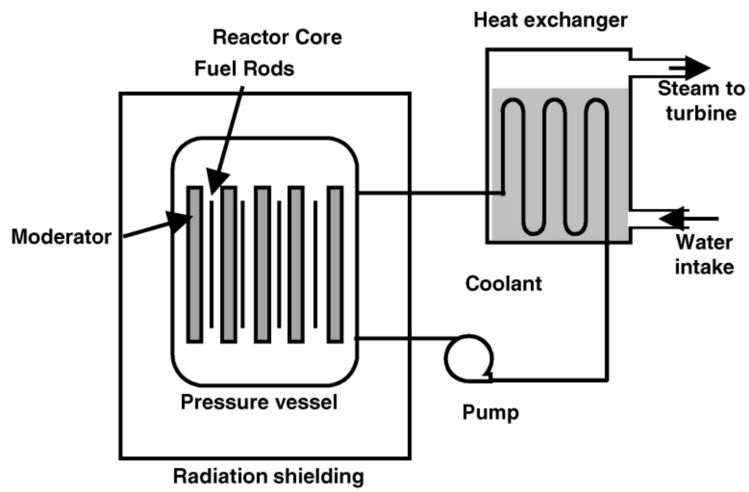

Figure 11.4 Schematic of a pressurized water reactor.

11.2.5.2. *Operating Principles and System Configurations.* Most nuclear power plants operate on the steam cycle described in Section 11.2.2.1, although new designs are being developed which operate on a gas turbine cycle. The heat for the boiler is provided by fission, the splitting of a heavy atom into multiple fission products and heat. The majority of nuclear power plants use enriched ${}^{235}_{92}U$ as the fissionable material for heat and steam generation rather than the combustion of a fossil fuel (coal or natural gas). Isotopes of uranium (such as ${}^{235}_{92}U$) and plutonium are able to undergo a fission reaction when bombarded by neutrons. The following is the average result of the many possible fission reactions of uranium 235:

$$1\,\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow \mathrm{F}_1 + \mathrm{F}_2 + 2.47\,\mathrm{n} + 203\mathrm{MeV} \quad (11.6)$$

Any given fission reaction will produce an integral number of neutrons and a given amount of kinetic energy of the product fragments, F_1 and F_2. This kinetic energy, quickly dissipated by interactions with the surroundings, produces heat (203 MeV) and neutrons (an average number of 2.47n per ${}^{235}_{92}U$ atom). A chain reaction can be sustained if more than one of the released neutrons is absorbed by another fissionable material. The likelihood of a neutron being absorbed is increased by using moderators (such as water) to slow the speed of the neutrons. Currently, there are four major configurations of nuclear power plants that are commonly used:

(a) *Pressurized water reactor* (*PWR*). Figure 11.4 shows a PWR. This is the most common type of reactor (57% of reactors worldwide). Water is used as both the moderator and coolant. The coolant water is in a separate loop from the working fluid of the steam cycle to prevent any radiation-contamination of the steam cycle equipment. Commercial PWR power plants range from 600–1200 MW and can contain over 50,000 uranium fuel rods in the core.

(b) *Boiling water reactor* (*BWR*). This is the simplest type of nuclear reactor. BWRs account for around 21% of reactors worldwide. Instead of having two separate loops—one for the coolant water and another for the turbine water—they are combined to one loop. This is essentially a steam plant with a nuclear reactor-based steam generator. BWRs require a larger pressure vessel volume and radioactivity leaking from the fuel rods to the coolant water can be transferred to the turbines. Installed plant sizes range from 600–1400 MWe.

(c) *Gas cooled reactor* (*GCR*). It uses CO_2 rather than water as the coolant. A variant, called the *high-temperature-gas cooled reactor* (HTGCR) operates at a fairly high temperature, which allows for superheating and reheating modifications of the basic steam cycle. Advanced designs of each of these types of reactors improve reactor safety and power density, simplify the plant design, and reduce construction costs. Additionally, there are new designs that operate with gas turbines rather than steam turbines.

(d) *Pebble-bed reactor.* This advanced design uses small tennis ball sized fuel pebbles instead of fuel rods. Helium gas is used as a coolant and is expanded through a gas turbine, which is able to operate at much higher temperatures, increasing efficiency.

11.2.5.3. *Efficiency Considerations.* Most nuclear plants operate on the Rankine cycle and are thus akin to fossil fuel steam power plants. The heat addition temperature, in part, determines the thermal efficiency of the cycle, and the efficiencies of PWR and BWR nuclear power plants are limited because of the low steam generation temperatures (~ 300 °C) needed to maintain a moderate reactor coolant pressure (70–200 atm). The thermal efficiency is thus around 32%. Another aspect of efficiency is fuel burn up, which indicates the extent to which heat is extracted from the uranium. The fissionable products in a fuel rod are not completely reacted before the fuel is replaced because of problems with fuel damage, production of gaseous fission products, and corrosion problems. As a result, some heat energy is left unutilized and lowers the ultimate fuel energy conversion efficiency.

11.2.5.4. *Environmental and Public Concerns.* There are significant environmental and safety concerns surrounding the use of nuclear power to generate electricity. Its proponents argue that it is a well-established carbon and air pollution

free means of generating electricity. Nuclear power accounts for the largest non-fossil fuel based energy conversion in the world. With the large uranium reserves in the world and the possibility of developing fast breeder reactors, nuclear power is attracting more proponents, especially because of the increasing realization that CO_2 emissions need to be curtailed, and the environmental and health impacts of air pollution. Its opponents cite the main drawbacks of nuclear power—reactor safety and nuclear waste. Accidents at Three Mile Island in the USA and Chernobyl in Ukraine highlight the dangers of catastrophic accidents in a large nuclear power plant, including core meltdown and a large release of radiation. In the Chernobyl accident, 31 people died at the plant and several thousand deaths from cancer are attributed to the radiation release. Spent fuel from power plants is highly radioactive and needs to be quarantined from human contact for several thousand years. Finding a suitable storage facility has not been without controversy—both scientific and political. With respect to nuclear weapons proliferation, only a small quantity of fissionable material (~ 10 kg) is required to build a nuclear weapon and most power plants produce several hundred kilograms per year.

11.2.6. Hydroelectric Power Plants

11.2.6.1. *Operating Principles.* Hydropower is a clean and abundant energy source that relies on the hydrologic cycle. Water evaporates from the oceans and lakes and returns as precipitation. Some of this precipitation flows through rivers, lakes and reservoirs and the energy from this flowing water can be controlled and harnessed to provide mechanical energy and ultimately electricity. Hydropower was first developed during the Roman Empire by channeling water onto a water wheel to generate mechanical power for irrigation, milling, and other operations. In the middle of the 19^{th} century, the hydraulic turbine replaced the water wheel. Hydroelectric power plants contribute about 20% of total worldwide electricity generation.

Large-scale hydroelectric power plants are typically sited where flowing water can be stored in reservoirs and controlled. The potential for useful and economical energy conversion depends on location, landscape and topography, and stream flow characteristics. The stream characteristics in turn, depend critically on the rainfall pattern and the watershed area (the area of land that contributes to flow in a given stream or river). The essential components of a utility-scale hydroelectric power plant are (Figure 11.5):

- a *reservoir/dam* that stores the water and blocks the downstream end of the reservoir;
- a *spillway* (or flood discharge structure) which controls the water level and the flow of water;
- *tunnels and penstock*, which transport the water to the turbines;
- a *turbine and generator* to convert the potential energy of the stored water into shaft work and finally electricity; and

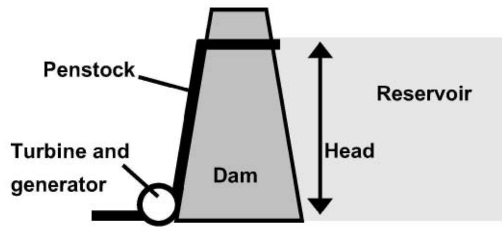

Figure 11.5 Essential components of a utility-scale hydroelectric power plant.

- a *surge tank*, located between the tunnel and penstock or between hydraulic machine and tail water tunnel to dampen fluctuations in water pressure and level.

Hydraulic turbines are designed to use both the potential and kinetic energies of the water to convert it to mechanical energy.

11.2.6.2. *Performance Characteristics.* Hydroelectric power generation involves the conversion of the potential energy of water, with a mass, m, and height, h, to kinetic energy and then electric energy. Thus, assuming a 100% energy conversion and mass flow rate $\dot{m}$, the electrical power generated (P) is given by:

$$P = \dot{m}gh \tag{11.7}$$

where g is the gravitational constant.

Including the turbine (η_T) and generator (η_G) efficiencies, the power is:

$$P = \eta_T \eta_G \dot{m}gh \tag{11.8}$$

The installed capacity is the designed maximum power from the turbines. In principle, there should be very few efficiency losses during power generation because turbine and generator efficiencies can be quite high. Large hydroelectric plants can have total efficiencies up to 90% but for small hydropower plants efficiencies could vary from 40–70%. Since precipitation patterns can be intermittent, the presence of a reservoir can mitigate some of the seasonal fluctuations in stream flow and allow continuous power generation.

11.2.6.3. *System Aspects and Economics*. Hydroelectric plants have been built in many sizes, from large hydro (> 100 MW) to small hydro (1–30 MW), mini- (100–1000 kW) and micro-hydropower (< 100kW). In 1997, the worldwide installed capacity was 660 GW, most in large hydropower plants (> 96%). Large-scale hydroelectric power generation often involves high transmission costs because of the remote location of these plants. The most attractive sites for hydropower in the USA have already been developed, while other potential sites are less attractive because of higher costs or environmental reasons.

An interesting variation on hydroelectric power, i.e., pumped storage, (which accounts for about 14% of all US hydropower) uses two reservoirs at different heights to store water during off-peak times and generate hydropower during peaking hours, when electricity generation is most expensive. In this system, the cheap, excess electricity is used to pump water from the lower reservoir into the upper reservoir, and this stored water can be used to drive the turbines when the electricity is needed. It appears unlikely that pumped storage will increase significantly because of the lack of suitable sites near large power plants.

The construction of hydroelectric power plants is capital intensive—capital costs vary widely, but generally are between \$1000 and \$3000/kW. However, since there are no fuel costs, the cost of electricity can be relatively low, i.e., \$0.02 to 0.08/kWh from large plants and \$0.03 to 0.10/kWh from smaller plants. Though this is a mature technology with a long history of implementation, advances can still improve dam structures and materials, turbines, generators, sub-stations, transmission lines, and environmental mitigation technologies, reducing costs and environmental impacts.

11.2.6.4. *Environmental Benefits and Concerns.* Hydroelectric power generation is apparently attractive because it is a clean, efficient, non-polluting, renewable energy system. In fact, it is the most advanced and mature renewable energy technology. Once constructed, these systems release almost no pollutants and require no fuel on resource use. Dams and the resulting reservoirs have other benefits including flood protection, stream-flow control, and recreation opportunities. However, there is an increasing awareness of a host of ecological and environmental consequences of building dams and creating large reservoirs. These major impacts may be summarized as follows:

- *Dam construction impacts.* Building large-scale hydropower plants involves construction of large dams, excavating underground channels, and the construction of large structures to house generators.
- *Ecosystems.* Large scale changes in water conditions like temperature and salinity can affect aquatic biodiversity, disrupt spawning runs, flood large land areas, and reduce the sediment load of a river.
- *Human displacement.* The construction of the Three Gorges Dam is expected to displace several million families and flood whole cities. The estimated cost is \$25,000/family.

11.2.7. Photovoltaic Power Generation

11.2.7.1. *Background and Operating Principles.* Currently, photovoltaic cells account for a tiny fraction (about 0.03%) of electricity generation in the USA, but solar panel manufacturing increased by about 20% annually during the 1990s. Worldwide annual production is approximately 400 MW/year and cumulative capacity is approaching 2 GW. Like the fuel cell, the photovoltaic or solar cell is a direct energy converter; in the latter case, visible light is converted directly into electricity.

Photovoltaic energy conversion occurs by exposing various configurations of a diode p-n junction to light; a semiconductor with a positively doped p-layer contains mobile positive charges or holes in contact with a negatively doped n-layer, which contains mobile electrons. A diode electric potential is attained when the electrons of the n-type move to fill the holes of the p-type and the p-type region becomes negative and the n-type region positive. When a photon with sufficient energy collides with an electron, it creates a free electron and a hole. When this process occurs near a p-n junction, the field will push the hole to the p-type side and the electron to the n-type side. If the two regions are connected through an external load, a current flows though it, allowing the electrons to reunite with the holes. This current flow across the cell electric field potential generates electrical power.

A typical device is made by diffusing a p-type material (e.g., B) into a heavily doped n-type (e.g., As into Si) wafer to form a p-film layer, a few μm thick. Electrical contacts to the p and n types are made by electroplating a metal (e.g., gold or copper) on each region. To achieve the desired DC power levels, photovoltaic cells can be connected in series and parallel; AC power can then be generated by using an inverter.

There are two types of solar cells–crystalline and amorphous. The former is made from silicon wafers, sliced from rods or blocks, and can either be monocrystalline or polycrystalline. Amorphous or thin film cells are made by depositing a thin layer (~ 1μm) of silicon on a substrate (glass or plastic). Silicon solar cells make up 95% of solar cells and are the most developed and commercialized types of photovoltaic cells. Other types of solar cells being developed use doped semiconductor materials like GaAs, CdTe, and $CuInSe_2$. Organic semiconductor cells are in the research stage and dye-sensitized TiO_2 cells are gaining momentum.

11.2.7.2. *Performance Characteristics.* Theoretically, with monochromatic light as the energy source, photovoltaic cells can achieve 100% efficiency. However, due to the radiation spectrum of sunlight, photons with less than the band gap energy cannot create electron-hole pairs, but instead create heat. Photons having energy greater than the band energy can generate electrons and holes; but because these photons will have more energy than the mean free energy of the carriers, only the energy corresponding to the band gap generates electricity while the excess energy is dissipated as heat. The theoretical maximum efficiency

for crystalline Si cells exposed to sunlight is approximately 28%. Other inefficiencies are due to optical shading and cell and electrical contact resistance. Monocrystalline silicon can achieve about 24% efficiency in the laboratory while manufactured solar modules achieve around 15% efficiency. Polycrystalline Si solar cells can also achieve an efficiency of about 14% in real world manufactured solar modules. Amorphous silicon solar cells have much lower efficiencies—about 13% in the laboratory and 6% in manufactured cells.

11.2.7.3. *Systems Aspects and Economics.* Solar insulation can exceed 1 kW/m^2 on a flat surface on a clear, sunny day. However, the insulation will vary throughout the day with the sun's position, as well as the angle of incidence. Under the best circumstances, it is possible to average over 300 W/m^2 over the course of the day, which, given a 15% efficient photovoltaic system, translates to an average power output of 45 watts per m^2. It is therefore necessary to cover large areas with solar cells to generate significant power levels. Tracking systems can allow the panels to follow the sun and consequently capture slightly more incident radiation. Because photovoltaic cells only operate when sunlight is available, providing electricity during the night or during cloudy days requires another energy supply, as illustrated in Figure 11.6. In a small-scale hybrid system, excess electrical energy generated by the photovoltaic system is stored by charging a secondary battery. In grid-connected systems, the grid itself can be used as a backup. Excess solar electricity generation can be fed to the grid (via an inverter) and when demand exceeds generation, electricity can be obtained from the grid. In the USA, most states have some type of net or dual metering laws for residential customers to

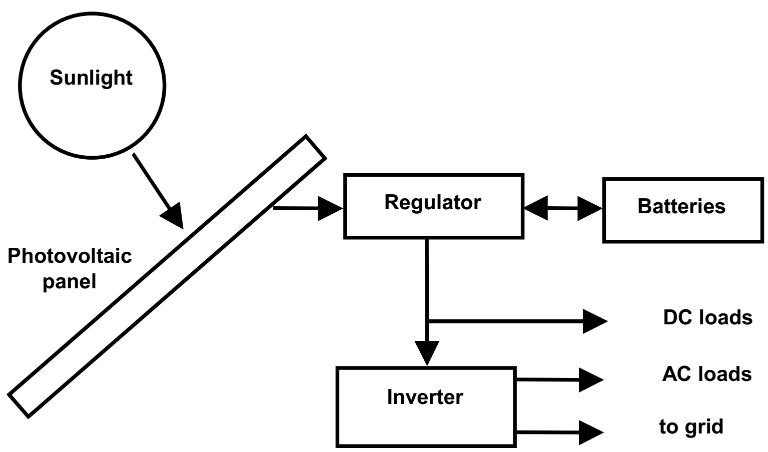

Figure 11.6 Schematic of photovoltaic solar-power system.

facilitate the two-way flow. Despite the intermittency of solar energy, one benefit is that electricity is produced precisely when it is needed—air-conditioning peak demand corresponds with hot, sunny, summer afternoons.

Typical crystalline solar cell module costs are about \$3.50/watt. The capital cost for the entire system depends on the type of photovoltaic system used. For example, costs can increase significantly if battery energy storage is added. The cost of electricity for renewable energy systems depends strongly on the capital cost of the energy conversion device, since there are no fuel costs and very low operation and maintenance costs. Thus, electricity costs for solar are currently quite high (\$0.20–0.50/kWh) because of the high capital cost of the photovoltaic and energy storage systems and the low capacity factor (< 25%).

11.2.7.4. *Environmental Benefits and Concerns.* Along with wind energy, photovoltaic systems are one of the most environmentally acceptable energy sources. It is a renewable energy technology that generates electricity without the use of fuel or other resources, and without emissions, such as CO_2. There are some fossil energy uses (amounting to as much as 10% of total expected energy generation) and pollutant emissions (CO_2, lead, CFCs, and chlorinated products) during the production of solar cells. One of the greatest disadvantages of photovoltaic systems is the large area of land required for electric power generation. Solar energy is a diffuse energy resource: 3 to 10 km^2 is required for a 100 MW plant, with the total amount of electricity generated per year being 180 GWh/y compared to an equivalent annual energy production from a 30 MW thermal power plant and a land area of about 0.01 km^2. However, incorporation of solar photovoltaic systems into rooftops and other building materials can essentially eliminate the land requirements and provide distributed generation at the point of demand.

11.2.8. Solar-Thermal Systems

11.2.8.1. *Background and Operating Principles.* A solar-thermal power plant uses solar radiation to produce high temperature heat that drives a heat engine cycle (as described earlier in this Section) to produce electrical energy. Solar thermal power plants use reflectors and collectors to concentrate the sunlight onto a small area, which significantly enhances the temperature. The heat is collected by a working fluid and is coupled to a heat exchanger to drive a vapor power cycle. Solar thermal power plants have been confined to desert areas, with a high fraction of sunny, cloudless days. The installed, worldwide capacity is small, approximately 400 MW, and the amount of electric energy generated annually is about 1 TWh. Solar-thermal systems can also produce hot water and steam for industrial applications.

Several configurations of the thermal power plant have been developed. In each of these systems, there are four basic sub-systems: collector, receiver, transport and storage, and power conversion (Figure 11.7). The collectors or concentrators can

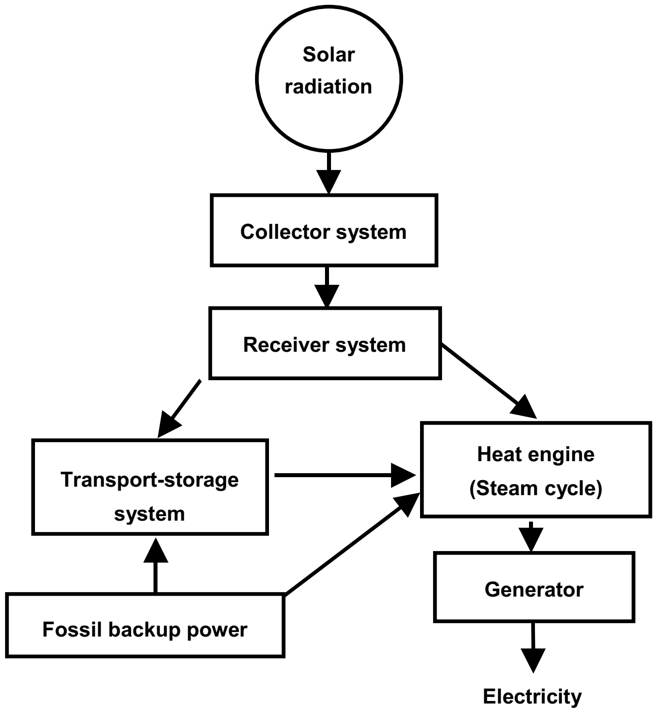

Figure 11.7 Schematic of solar-thermal power plant.

take sunlight from a larger area to focus it onto the receiver. The receiver is the system where the solar radiation is converted into heat and carried away by the working fluid, the heat transport and storage system. Finally, the power conversion system is a conventional Rankine vapor power cycle. The different configurations which have been developed are:

- *Parabolic-trough system*. This system uses a parabolic mirror with a receiver pipe at the focus of the parabola and can reach temperatures up to 350 °C.
- *Parabolic-dish system*. It uses a tracking dish reflector to concentrate the sunlight onto the receiver, again at the focal point, and can reach temperatures up to 1000 °C.
- *Central-receiver system.* This system uses sun tracking mirrors (heliostats) to reflect solar energy to a receiver at the top of a tower. Because of the large collector area, the central receiver configuration can generate temperatures up to 1500 °C.

In each of these systems, the working fluid is transported to the power conversion system to generate electricity. Often, the solar heat is backed up or supplemented by a fossil fuel boiler.

11.2.8.2. *Performance Characteristics.* The conversion efficiency from solar energy to electricity may be expressed by the equations:

$$\eta = \frac{\textit{Net Electrical Output}}{\textit{Solar Input to Collector}} \tag{11.9}$$

$$\eta = \eta_c \eta_r \eta_t \eta_e \tag{11.10}$$

where η_c is the efficiency of the collector system that depends on its reflectivity; η_r is the efficiency of the receiver, the ratio of the energy absorbed by the working fluid to the energy incident on the receiver; η_t is the efficiency of the transport system; and η_e is the steam-cycle electrical-conversion efficiency determined by the temperature of the working fluid. Another important aspect is the capacity factor, which is typically around 20% for solar thermal plants. Solar insulation is relatively diffuse. Even with concentrating reflectors, the overall efficiencies of solar-thermal electrical power plants are about 15%, which is considerably less than the efficiencies of conventional thermal plants using fossil fuels.

11.2.8.3. *Systems Aspects, Applications, and Economics.* The Solar Two power plant, operated by Southern California Edison in the USA, can supply, on demand, power generation because thermal energy storage in a molten salt enables it to provide continuous power. The rated capacity of this plant is 10 MW. Solar thermal systems can also be coupled with conventional thermal boilers using fossil fuels to provide a continuous supply of electricity. Projections from the World Energy Assessment are that total solar thermal power generation will increase to 2 GW by 2020.

Projections for the cost of trough-based power plants are \$3000–3500/kW, while the estimated cost for central receiver systems is in the range \$4700–5000/kW. It is projected that in the long term these costs will decrease by 30 to 50%. The levelized energy cost is expected to be \$0.14 to \$0.18/kWh in the near term and could be reduced to \$0.04 to 0.06/kWh in the long term, although this cost requires a credit of \$25–40/ton for reduced CO_2 emission.

11.2.8.4. *Environmental Benefits and Concerns.* Similar to wind and photovoltaic solar cells, solar thermal power plants do not generate any pollutants during electricity generation. They rely on solar radiation that does not require any resource extraction. However, the land requirements can be extensive; a 20-MW plant will use about 1 km^2 of land area. Typical locations for installations are in the southwestern USA and the Middle East. Desert environments can be quite fragile,

and the installation of large dispersed power plants can impact the ecology of these areas.

11.2.9. Wind Energy Systems

11.2.9.1. *Background and Operating Principles.* Solar radiation is the primary source of atmospheric convection and consequently of wind energy. The uneven heating of the earth's surface leads to pressure differences and these convection currents. Using wind turbines, energy in the wind can be converted to rotating mechanical energy and coupled to generators, where it is converted to electrical energy. The exploitation of wind energy to do mechanical work, such as turning millstones or pumping water, dates back well over 2000 years. Significant development on modern wind turbines around 1980 has led to rapid growth and advances in wind energy systems. Currently, wind accounts for about 0.2% of electricity generation in the US, and there is an installed capacity of about 2 GW, most of it in California. Significant cost reductions and technology improvements in the last decade have spurred development of wind energy "farms" globally, and a significant growth rate of installed capacity (30–40% annually over the last few years in Europe and the United States).

Wind turbines extract power from the wind by taking advantage of aerodynamic lift as the wind passes over the wing-like turbine blades. Higher wind velocities on the curved side of the blade will lead to a lower pressure, and the pressure differential generates the necessary force, perpendicular to the flow, to turn the rotor. The power density (W/m^2) of the rotor area of a wind stream, P, is related to the cube of the wind velocity:

$$P = \frac{\rho v3}{2} \tag{11.11}$$

where ρ is the air density and v the velocity of the wind. The theoretical maximum power, $P_{max,}$, which can be extracted from the wind is only about 60% of the total wind power density:

$$P_{\max} = 0.592P \tag{11.12}$$

It is impossible to extract all the energy out of the wind, since the air leaving the turbine must have some velocity (i.e., kinetic energy).

As illustrated in Figure 11.8, a wind energy system is composed of the following components:

- *rotor/blades,* which extract kinetic energy from the wind to turn the turbine shaft;
- *generator* to convert the shaft work to electricity (AC or DC);

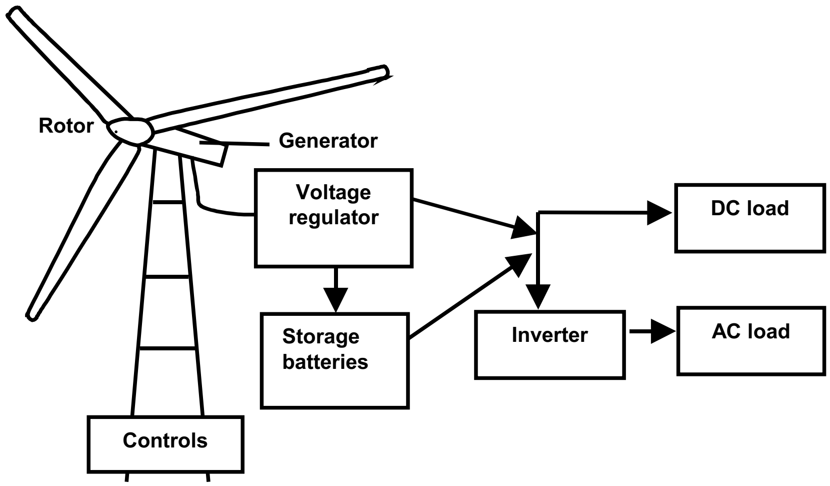

Figure 11.8. Schematic of a small hybrid wind energy system.

- *tower* to support the blades and generator at a suitable elevation; and
- *power converter/controller* to ensure the acceptable electrical output.

Advanced systems can also have a *yaw controller* to maintain optimal orientation of the rotor into the wind. There are two types of wind turbines: horizontal-axis and vertical-axis systems. The vertical axis wind turbine (such as the Darieus rotor) has the advantage that the drive train, generator, and controls are at the ground level for easier design, installation, operation, and maintenance. However, wind velocities increase with the height of the wind tower and higher power is more easily achieved with the horizontal-axis systems.

11.2.9.2. *Performance Characteristics.* The energy output of a turbine depends on the wind speed distribution and surrounding terrain. Because of the cubic relationship between power and wind speed, it is difficult to estimate the average power expected from a wind turbine using the average wind speed; knowledge of the details of wind speed distribution is necessary for this estimation. Wind resources are categorized by the average wind speed; a class 6 or 7 resource is a very windy location and has average wind speeds of 18–27 mph, which yields a wind power density of 0.5–2 kW/m^2 at a height of 50 m. On average, it is possible to capture only about 20–30% of the rated capacity (capacity factor), because of the intermittency of wind resources. The efficiency of a turbine is also optimized for a specific design wind speed; peak efficiency can reach 40–50%. The efficiency decreases with deviations from this design speed. High wind speeds can cause

significant damage to the rotor, turbine, and generator; under such conditions, the excess energy must be dissipated by braking or by changing blade/rotor orientation. This "cut-out" wind speed is typically around 55 mph.

11.2.9.3. *Systems Aspects and Economics.* Wind turbines are found in many sizes. Some DC wind turbines, with rotor diameters of less than 1 m are capable of electric power generation up to 500 W. Some of the largest wind turbines have rotor diameters of over 70 m and are able to generate over 2 MW. Large wind turbines are typically grid connected and are often combined with transmission systems to maintain constant shaft speed to generate 60 Hz AC electricity. Small wind-energy systems offer several possible configurations depending upon the application:

- *hybrid systems*, in which wind turbines are coupled with another power source such as a generator or energy storage (Figure 11.8); and
- *grid-connected systems* which supply power to a house or cabin but use the grid for storage and backup power.

Since wind energy is typically intermittent, coupling the turbine with an energy storage system or the grid is required for constant and continuous power. The intermittency of wind power is important when considering large-scale wind power generation. Because wind power has a low capacity, increases in wind power generation to a significant fraction of total electricity generation would have to be coupled with breakthroughs in low-cost energy storage or long-distance transmission.

The economics of wind systems depends significantly on the installed cost of the wind turbine, as well as on the nature of the wind resource. Because there is no fuel cost and operational and maintenance costs are fairly low, the price of electricity is mainly determined by the amortized cost of the turbine divided by the annual electricity output. The capital costs will vary somewhat depending upon location and installation costs, while the annual electricity production can vary significantly with location. Typical turbine costs are around $700–1000/kW, excluding costs of other system components or installation. Electricity costs are expected to be below $0.04/kWh in the windiest locations (class 7 resources) and between $0.04–0.07/kWh for more moderate wind resources.

11.2.9.4. *Environmental Benefits and Concerns.* Wind turbines operate very cleanly, requiring no fuel and little maintenance, and their construction does not require any special materials or processes. They produce no pollutant emissions or greenhouse gases, require no fuel or other resources for operation, and use a truly renewable resource. As a result, they are touted as an important and economical means to reduce the environmental impacts of electricity generation. However, the main concerns that are raised have to do with the following:

- aesthetics and visual disruption of scenic landscapes and coastlines;
- sound produced by the wind turbine; and

- effects on bird migration and collisions of birds with the towers or rotor blades.

Research efforts into larger wind turbines yield slower, more silent rotor blades, which produce more power and thus require fewer towers. Other strategies include siting windfarms far offshore to minimize any visual impact, noise, and effects on birds. Given the significant environmental benefits of wind power, technical improvements and further studies should minimize these concerns.

11.2.10. Geothermal Energy Systems

11.2.10.1. *Background and Operating Principles.* The molten core of the earth and radioactive decay of materials in the earth give rise to abundant thermal energy, which moves to the earth's surface. This energy is quite diffuse (on average 0.1 W/m^2) but can also be found concentrated in specific locations around the globe near tectonic plate boundaries and hot-spots. In these locations, hot springs have been used for bathing and washing for thousands of years. At the beginning of the 20th century, geothermal energy systems were developed for space heating, industrial process heat, and electric power generation. Currently, the geothermal power generating capacity in the USA is 2.8 GW (around 0.3%) and is 8 GW world-wide. Some have estimated that a significantly higher capacity can be developed for electric power generation: 25–50 GW in the USA and over 100 GW in the rest of the world. Steam and hot water reservoirs make up only a small part of the useable geothermal resource. Magma and hot dry rock are also useful sources of thermal energy. The basis for electricity generation is the steam cycle, using the geothermal energy to supply steam (i.e., the boiler). The steam is expanded through a turbine driving an electrical generator. In addition to electricity generation, excess steam or hot water can be used for other purposes, such as process heat and space heat.

11.2.10.2. *Performance Characteristics and System Configurations.* There are three main types of geothermal-steam-power plants, depending upon the source of heat available:

- *Dry-steam plants* use steam piped directly from below the surface to drive a turbine, and the condensed water is returned via an injection well;
- *Flash-steam plants* pump pressurized high temperature water to the surface, where it is injected into a tank in which it quickly vaporizes because of the pressure drop. The energy of its expansion is then captured by the turbine; and
- *Binary-cycle power plants* use lower temperature water (< 200 °C), to vaporize another lower-boiling-point working fluid (in separate loops), which in turn drives a vapor-power cycle. Moderate-temperature geothermal heat is the most common source and binary cycle systems are being built to exploit them. Hot, dry rock is a more available geothermal

source than hot water or steam, and can potentially be exploited by crushing the rock to improve heat transfer and then injecting water into these areas.

Geothermal-electric-power systems use a vapor-power Rankine cycle. For most geothermal systems, steam is delivered at temperatures around 200 °C, and the efficiency is in the range of 5–20%, which is lower than for fossil fuel-fired thermal power plants. The efficiency for the direct use of thermal energy is between 50 and 70%.

11.2.10.3. *Systems Aspects and Economics.* The potential sites for geothermal electric power production are limited to specific areas near plate boundaries and volcanic areas. Typically, geothermal power plants have very high capacity factors (~ 95%) because of their simplicity and constant heat supply. One problem is that geothermal reservoirs may be finite and as heat is extracted, the quality of heat declines and the resource may become worthless. The capital cost of geothermal power plants is in the range of $800–3000/kW and the cost of electricity will depend on the quality of the geothermal resource, but some of the best sites can achieve a cost of $0.05 to 0.10/kWh. The viability of cogeneration from geothermal power plants is site-specific, because steam or hot water from geothermal resources cannot be economically transported over long distances.

11.2.10.4. *Environment Emissions Concerns.* Geothermal energy conversion systems are another example of a clean, renewable resource. They require no fuel supply and typically require less space to operate than a comparably rated coal power plant. They can reduce greenhouse gas (GHG) emissions significantly, but they are not zero. Dissolved gases in geothermal fluids are mostly N_2 and CO_2, with some H_2S and smaller amounts of NH_3 and radon, which can be released to the atmosphere. Binary cycle systems are typically closed loop systems and the amount of dissolved gas released can be minimized. There are also small amounts of Hg and B found in the water. Most of these impurities are reinjected into drill holes. The H_2S is removed by hydrodesulfurization. The amount of CO_2 released during geothermal power plant operation depends on the geothermal fluid properties but can be expected to be about one tenth the amount released from a fossil fuel plant (500–1000 g/kWh).

11.2.11. Ocean Energy Systems

11.2.11.1. *General Comments on Types of Systems.* Like solar radiation, the ocean is another widely available and distributed energy source. The energy in the ocean is in part kinetic energy in the form of tides, currents, and waves, and part thermal energy from the sun stored as heat. The quantity of energy stored in the ocean is enormous but can be quite diffuse; in some cases, it is about

the same as from solar radiation and, as a result, it is difficult to harness. Marine energy systems can be classified into four main groups:

- Tidal-barrage energy
- Wave energy
- Tidal/marine currents
- Ocean thermal-energy conversion.

The following Sections briefly summarize some of the interesting aspects of these technologies.

11.2.11.2. *Tidal-Barrage Energy Systems.* This type of energy system is equivalent to a low head hydrosystem and makes use of the rise and fall of the tides. A dam is built to separate the open water from a reservoir and the changing tides will drive water through the turbines. Electricity can be generated by water flowing either way. Also, the system can be used for pumped storage for cheap off-peak electricity. A 240-MW electric-generation power plant was built in France in the 1960s. There have been plans to design and build GW size plants in the Bay of Fundy in Canada and in the Severn estuary in Great Britain, but the costs are expected to be extremely high. Though such a system does not emit environmental pollutants, the effects on a tidal estuary and on the complex and often fragile ecosystem are poorly understood.

11.2.11.3. *Wave Energy Systems.* Waves are a source of kinetic energy, which can be converted via a generator to electrical energy. Technologies have been developed to exploit wave energy offshore, as well as along the shoreline, but most demonstration units have been built along the shoreline because of the relative simplicity. There are several types of shoreline wave energy units but each relies on the periodic nature of waves. The oscillating water column device uses the vertical motion of the wave to compress an air column and drive a turbine. A tapered channel device uses wave energy to move water into an elevated reservoir, where it can be used to drive a turbine. These systems can be used to drive electrical generators.

11.2.11.4. *Tidal Marine Currents.* Tidal power energy from ocean currents can be converted to electrical energy using large submerged turbines. Since the motion of sea water is rather slow in most places, the amount of power/energy, which can be extracted, is small; this is due to the cubic relationship between velocity and power. Grid connected systems are being investigated. The turbine designs are similar to those for wind turbines. Marine-current turbines should operate near to the surface, where the velocity is highest.

11.2.11.5. *Ocean Thermal- Energy Converters (OTEC).* OTEC systems are heat engines that rely on the temperature difference of the ocean at different depths to drive a Rankine (steam/vapor) cycle. Warm seawater is heat exchanged

with a low-boiling temperature fluid such as ammonia. There are several challenges in developing large systems:

- the need to circulate large volumes of sea water through pipes,
- the small temperature change between source and sink, limiting the theoretical efficiency for thermal to electric energy conversion which at best is of the order of 7% in a practical system and less than half of this value, and
- the need to lower the cost of transmission of electricity to the land.

11.3. SMALL-SCALE REMOTE AND DISTRIBUTED POWER

11.3.1. Background

This category comprises generators with outputs ranging from a kilowatt to several megawatts. In very remote locations, access to the electric power grid may not be cost-effective or even possible. Remote power refers to small-scale stationary applications that rely on electricity generated from these devices as their primary supply. Examples of these applications are telecommunications relay stations, remote industrial operations (e.g., mining, oil drilling/exploration), water pumping, remote village power, and exotic systems for powering satellites and space probes. Distributed power refers to any small scale power generation that can be sited closer to the end-user than a typical large scale power plant and may be connected directly to the end user or to the utility distribution system. Specific benefits of distributed generation include high reliability standby and premium power, peak-shaving, baseload generation, and cogeneration. Its use may delay the need to upgrade transmission and distribution systems.

11.3.2. Small-Scale Generation Technologies

11.3.2.1. *General Comments.* Distributed and remote power technologies include many small-scale versions of technologies described in Section 10.2. These include gas-fired microturbines, solar photovoltaic (PV) systems, wind turbines, and engine generators. The remote power technologies may also include energy storage (i.e., batteries) for the intermittent renewable sources in order to provide continuous power. Power generation technologies that require fuels (i.e., diesel or natural gas) may not be suitable for some remote locations because of the cost and logistics of delivery.

Power customers such as hospitals, computer servers, financial institutions, research laboratories, and factories may need high-reliability power because of the critical nature of their business and the high cost of power disruptions and outages. Siting a small-scale plant nearby or operating their own generator (either as primary

power or backup) often makes sense for backup systems for manufacturing plants. For applications that also need heat, turbine, engine, or fuel cell waste heat can often be a useful co-product along of the electricity.

11.3.2.2. *Reciprocating Engines.* Internal-combustion engine generators (e.g., spark ignition and diesel) are the most widely used and mature distributed power generation technologies. The details of their operation are described in the next Section on transportation power plants. These engines are coupled to a generator to provide electricity. They can operate on natural gas, gasoline, diesel fuel, and even landfill/digester gas. Depending upon the size and power output of these engines, the efficiency can range from 25–45%, the higher efficiencies being from larger diesel engines. Emission controls are necessary to reduce the NO_x and CO emissions. Some systems are capable of cogeneration.

11.3.2.3. *Microturbines.* Microturbines are smaller versions of traditional gas-fired turbines (described in Section 11.2.2.2) ranging from tens to hundreds of kilowatts and are very close to commercialization with extensive demonstration and field testing. Typical microturbines use radial flow, have a single stage, and include recuperation to recover some waste heat and boost turbine inlet temperatures. Efficiencies for these microturbines can be as high as 25–30%. They can operate on natural gas, propane, hydrogen, or diesel. Cogeneration is possible with the production of hot water (50–80 °C) and overall efficiencies can be as high as 85%. In general, microturbines are generally compact and light weight, with high reliability and low (NO_x) emissions. Efficiencies without cogeneration, however, are not as high as larger gas turbines or combined-cycle systems.

11.3.2.4. *Renewable Sources.* Wind turbines may be used for remote and distributed power applications if the users are located in windy regions. Another renewable energy system suitable for remote and distributed power is photovoltaic-solar power. These technologies are described in previous Sections. They will require energy storage systems to provide continuous power. Typical capacity factors are around 20–25% for photovoltaics and 20–40% for wind systems. However, these systems, which require no fuel and little maintenance, can be sited in appropriate locations that are fairly inaccessible if the resources are available. Small-scale hydropower is another renewable energy source available for remote and distributed power. Systems can range from less than one kilowatt to many megawatts. Smaller systems do not require damming or even significantly change of the flow of rivers. Small systems, with low head, include low dams or weirs to channel water or simply “run of the river”. Because these systems may not be able to store significant amounts of water, their electric output may fluctuate with seasonal changes in river flow.

For outer-space applications, solar power is the only renewable source available, which is extremely important because of the difficulty and excessive cost

of transporting fuel into orbit for long-term missions. Many satellites and the international space station (ISS) use photovoltaic (PV) solar panels.

11.3.2.5. *Nuclear Sources.* Nuclear-power sources are used in some military and space applications where high energy density is a requirement for long durations and fuel cannot be resupplied. Nuclear fuels have over one hundred times greater energy density than chemical fuels. Nuclear powered submarines use the Rankine cycle to operate the ship propellers as well as to generate electricity. The use of nuclear power is beneficial for submarines where there is inadequate air for combustion. Other uses of nuclear power include nuclear heat sources to power thermoelectric generators. Thermoelectric power generation is based on the Seebeck effect, which causes a gradient of electric potential when the junctions of two dissimilar conducting or semiconducting materials (A and B) are maintained at different temperatures.

A thermoelectric generator is a heat engine and uses the temperature difference to generate electricity. Thus, the maximum efficiency is given by the Carnot efficiency:

$$\eta = \frac{T_1 - T_2}{T_1} \tag{11.13}$$

where T_1 and T_2 are the temperatures at the hot and cold junctions. Thermoelectric generators have no moving parts. Radioisotope-thermoelectric generators (RTG) rely on the radioactive decay of plutonium as their heat source and have flown on a number of NASA space probe missions including Cassini, Voyager, Galileo, Mars Viking, Mars Soujourner, Ulysses, and Pioneer.

11.4. TRANSPORTATION-AUTOMOTIVE POWER PLANTS

11.4.1. Perspectives

Transportation is another large energy consumer in the world. In the USA, transportation accounts for 28% of total primary energy use (automobile use constitutes about 23%.) The transportation sector also accounts for about one third of CO_2 emissions in the USA. The vast majority of cars and trucks are powered by the combustion of a hydrocarbon fuel in an internal combustion engine (either diesel or spark ignition). The transportation sector is interesting to investigate because it is a significant user of energy and because of its significant environmental impact. Fuel cells are, therefore, undergoing intensive research and development for use as power plants in transportation vehicles. Advanced vehicles and technologies such as electric vehicles and hybrid electric vehicles are also discussed in Sections 11.4.5. and 11.4.6.

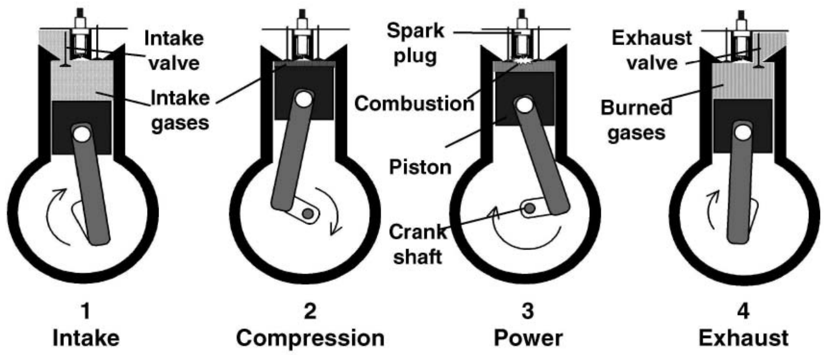

Figure 11.9 Sequence of steps in a four-stroke spark-ignition cycle.

11.4.2. Internal-Combustion Engine

11.4.2.1. *Design Types.* Invented in the latter half of the 19th century, internal combustion engines have been developed and refined for well over a hundred years. Designs are still being improved and the performance (power, efficiency, and emissions) can still be increased. The vast majority of automobiles are powered by a reciprocating (piston) internal combustion engine. They can be classified as operating under either an Otto cycle or a diesel cycle. The typical spark ignition engine, which is installed in the majority of passenger vehicles in the USA, is a homogeneous charge spark ignition engine. The air and fuel mixture are mixed before entering the combustion chamber, where ignition is initiated by a spark. Larger vehicles such as buses and trucks use Diesel engines because of their higher efficiency. These are stratified-charge compression-ignition (CI) engines, where air enters the combustion chamber and is compressed. Fuel is injected at the appropriate time and does not have a chance to fully mix with the inlet air before ignition is initiated by compression.

11.4.2.2. *Principles of Operation.* Most automotive engines are examples of four-stroke engines. Four stroke engines follow the sequence of steps in Figure 11.9. These may be briefly described as follows:

(a) *Intake stroke.* The inlet valve is opened and the piston is moved down to draw in the inlet charge (step 4 → 1).
(b) *Compression stroke*. The inlet valve is closed and the piston moves up to compress the inlet charge adiabatically (increasing pressure and temperature) (step 1 → 2).

(c) *Power stroke.* Combustion is initiated either by means of a spark or by the compression heating the mixture to the ignition temperature. The heat release raises the temperature and pressure applying a force on the piston and transferring kinetic energy to the crankshaft (step 2 → 3) ultimately powering the wheels.

(d) *Exhaust stroke.* The exhaust valve is opened and the piston moves up to push the burned gas mixture out of the cylinder (step 3 → 4). Figure 11.10 shows a pressure-volume trace for a four-stroke cycle.

11.4.2.3. *Work, Power, Efficiency, and Fuel Economy.* The net work of a given cycle will be equal to the pressure acting over the cylinder displacement:

$$dW = F \cdot dx = F / A \cdot Adx = P \cdot dV \tag{11.14}$$

During the power stroke, the high pressure burning gases will exert pressure on the piston transferring work to the piston and the crankshaft. During the compression stroke, the piston will be transferring work to adiabatic compression of the gases. Thus, the net work will be the difference between these two work values:

$$\text{Net work} = \text{Volume A} - \text{Volume B} \tag{11.15}$$

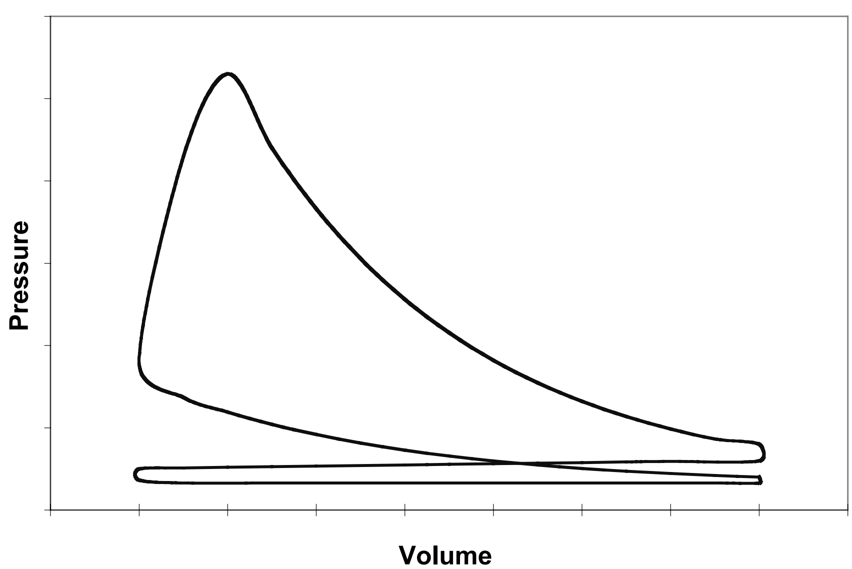

Figure 11.10 Pressure-volume trace for four stroke engine cycle.

The power would depend on the net work per cycle and the engine speed (rev/min). The thermal efficiency of an engine (η_t) is determined by dividing the net output work (W_{net}) by the heat (Q_{in}) added in the fuel combustion:

$$\eta_t = \frac{W_{net}}{Q_{in}} \tag{11.16}$$

The overall net work, power output, and thermal efficiency of the engine will depend upon the specific operating conditions of the engine, such as level of exhaust gas recirculation, spark-timing, turbocharging, fuel-air ratio, throttle conditions, fuel octane value, and engine load and speed. The fuel economy of a vehicle (typically measured in miles/gallon(mpg) or liters/100 km) is dependent on a number of factors including engine efficiency (as mentioned above), mechanical and transmission efficiency, type of drive cycle, vehicle aerodynamics and weight, rolling resistance, etc. The average fuel economy of US vehicles in 2000 was 16.9 miles per gallon, which is equivalent to 14l /100 km.

11.4.3. Internal-Combustion Engines: Spark-Ignition Engines

11.4.3.1. *Design and Principles of Operation.* The four-stroke spark ignition engine is a widely used example of the automotive combustion engine. Nearly all of the passenger cars in the US operate with a spark ignition engine. The fundamentals of operation, described in the last Section, will apply to both spark ignition and compression ignition engines.

The basic differences between a spark-ignition (SI) engine and other types of engines are based on the method of combustion initiation and of fuel-air mixing. In an SI engine, a spark plug is used to generate an electrical arc, which ignites the air-fuel mixture. This allows for precise control of the timing of the combustion event and can be altered under different circumstances. In addition, combustion in typical SI engines is initiated in a near stoichiometric premixed air-fuel mixture. The flame is initiated at the spark plug and propagates through the premixed gases. Heat release in combustion, which occurs fairly quickly, is aided by the turbulence of the intake gases; the pressure and temperature, attained during the power stroke, can increase rapidly before the piston expansion begins to extract energy and lower the pressure and temperature.

11.4.3.2. *Thermal Efficiency and Fuel Efficiency.* The theoretical efficiency of an ideal Otto cycle engine (assuming instantaneous heat release), which can approximate an SI engine operation, is based upon the compression ratio, r_c. The thermal efficiency (η_t) is given by:

$$\eta_t = 1 - \frac{1}{r_c^{\gamma-1}} \tag{11.17}$$

where γ is the ratio of specific heats of the working fluid at constant pressure and a constant volume. The overall compression ratio in SI engines is limited by knocking (unwanted compression-initiated ignition) in the unburned gas mixture. To limit knocking in high performance engines with increased compression ratios, high octane fuels are required. Typical compression ratios for a SI automobile engine are between 8 and 10, which thus limits the maximum theoretical thermal efficiency to around 50%. In practice, the efficiencies are considerably lower because:

- heat is not added instantaneously (and thus the maximum temperature and pressure are reduced from the ideal case),
- heat is lost to the environment, and
- energy dissipates via engine friction, which depends on engine speed.

Further, in order to meet emissions standards, exhaust gas recirculation (EGR) is utilized, which reduces the thermal efficiency. The best thermal efficiency achieved in the state of the art IC engines is about 35% without the use of EGR.

11.4.3.3. *Environmental Impacts: Emissions.* The most significant emissions from SI gasoline engines are CO, unburnt hydrocarbons, and NO_x (mostly NO). The NO_x contributes to tropospheric ozone production, which combined with hydrocarbon emissions produces photochemical smog. Exhaust gas recirculation (EGR) and varying the spark-timing decrease the maximum pressures and flame temperatures, and hence lower NO_x levels, but reduce the thermal efficiency. The levels of these three pollutants are also controlled by a catalytic converter which reduces NO_x and oxidizes CO and hydrocarbons. Current state-of-the-art engine and catalytic converter technologies are able to achieve very low emissions levels corresponding to the California emissions standards program LEV II (see Table 11.1). Other emissions include SO_2, due to small quantities of sulfur in gasoline.

11.4.3.4. *Typical Power Levels for Specific Applications.* Spark-ignition engines tend to be lighter and cheaper than diesel engines and are thus used for small to medium sized vehicles, typically in light duty or passenger applications. These range from motorcycles and scooters (from about 1–70 kW) to passenger cars and light trucks (20–200 kW). SI engines are also found in some small airplanes and helicopters. Gravimetric and volumetric power densities are approximately 0.15–0.5 kW/kg and 20–50 kW/l (displacement volume) respectively, at the rated maximum power. Power density may be increased with turbo-charging the engine, though the increased temperature and pressure could increase knocking, NO_x emissions, and materials issues.

TABLE 11.1
Emissions Standards as Set by the State of California's LEV II program.

LEV II exhaust mass emission standards for new 2004 and subsequent model LEVs, ULEVs, and SULEVs in the passenger car, light-duty truck, and medium-duty vehicle classes

Vehicle type	Durability vehicle basis (mi)	Vehicle emission category	NMOG (g/mi)	Carbon monoxide (g/mi)	Oxides of nitrogen (g/mi)	Formaldehyde (mg/mi)	Particulate from diesel vehicles (g/mi)
All PCs:	50,000	LEV	0.075	3.4	0.05	15	n/a
LDTs 8500 lb		LEV, option 1	0.075	3.4	0.07	15	n/a
GVW or less		ULEV	0.040	1.7	0.05	8	n/a
Vehicles in this	120,000	LEV	0.090	4.2	0.07	18	0.01
category are		LEV, option 1	0.090	4.2	0.10	18	0.01
tested at their		ULEV	0.055	2.1	0.07	11	0.01
loaded vehicle		SULEV	0.010	1.0	0.02	4	0.01
weight							
	150,000	LEV	0.090	4.2	0.07	18	0.01
	(optional)	LEV, option 1	0.090	4.2	0.10	18	0.01
		ULEV	0.055	2.1	0.07	11	0.01
		SULEV	0.010	1.0	0.02	4	0.01

11.4.4 Internal Combustion Engines: Compression Ignition (Diesel)

While spark ignition engines are the power sources for the majority of passenger cars and trucks, diesel engines are widely used for heavy-duty commercial vehicles, such as large trucks and buses. In Europe, diesel fuel-powered passenger cars are also extensively manufactured due to their higher efficiency. At the present time, more than 30% of new cars sold in Europe have diesel engines. They are also used in large marine propulsion and railway locomotives.

11.4.4.1. *Applications and Principles of Operation.* The fundamental operating principles of diesel engines are practically the same as those of SI engines. However, unlike the intake stroke of a SI engine, where a premixed fuel and air mixture enters the chamber, during the intake stroke of a diesel cycle, only air is drawn in. Fuel is injected later into the cylinder immediately before ignition. Another difference is that combustion is initiated by adiabatic compression of the fuel/air mixture. Diesel fuel needs the compression-ignition qualities (cetane number), which is not the case with high-octane fuels. Because the fuel is injected into the cylinder when the temperature and pressure are on the increase (i.e., during the compression stroke), the fuel is not completely mixed with air when combustion begins; the rate of heat release will be limited by the rate of mixing of fuel and air. The heat release occurs over a longer period of time during the power stroke and so the maximum pressure and temperature will not be as high as in a SI engine with the same compression ratio.

11.4.4.2. *Thermal Efficiency and Fuel Efficiency.* Because the rate of heat release for a diesel engine is slower than that in a SI engine, its pressure peak will not be nearly as large as in the latter; this results in a pressure-volume trace different from that shown in Figure 11.10. As a result, the ideal diesel cycle approximates that of heat addition at constant pressure. The theoretical efficiency of an ideal diesel cycle is:

$$\eta_t = 1 - \frac{1}{r_c^{\gamma-1}}\left[\frac{\beta\gamma - 1}{\gamma(\beta - 1)}\right] \tag{9.18}$$

where β is the ratio of volumes over which heat is added and pressure is constant. The term in the brackets indicates a term that is always larger than 1, so that the thermal efficiency is always lower than that of a SI engine for any given compression ratio. However, CI engines can operate at higher compression ratios because they rely on compression ignition to initiate combustion, and as a result, they are more efficient than SI engines. The compression ratio is limited to about 20–23 because of NO_x and soot formation, which thus results in a maximum theoretical efficiency of about 55%. In practice, large diesel engines in trucks can achieve thermal efficiencies over 40%. Another contribution to the higher efficiency

of diesel engines is the higher energy density of the fuel (~ 12% higher than gasoline on a volumetric basis).

11.4.4.3. *Environmental Impacts: Emissions.* Diesel engines are similar to gasoline spark-ignition engines in that some of the predominant pollutant-emissions are NO_x and hydrocarbons. However, of equal or greater significance for urban air quality and health are the emissions of particulates (soot) and SO_2. Diesel fuels have higher sulfur content and their chemical composition leads to increased particulate formation. Diesels typically run lean (excess air) and as a result, CO emissions are not significant. The NO_x formation rate can be reduced by altering the air to fuel ratio, fuel injection timing, exhaust gas recirculation (EGR), and compression ratio. Particulates and soot formation are dependent on the fuel composition, as well as on compression ratio. Particulate (PM) emissions can have significant impacts on public health and will be the limiting factor for the use of diesels in the future. Further, CI engines are relatively noisier than SI engines.

11.4.4.4. *Power Levels and Performance Factors.* Diesel engines are generally more expensive than SI engines but have longer lifetimes. Because of the higher compression ratios, diesels tend to be heavier and operate at lower speeds (and power). But since they operate more efficiently than SI engines, they are consequently used in applications where efficiency and the longer lifetime are important, including in heavy duty commercial applications like large hauling trucks, agricultural equipment, construction equipment, locomotives, and boats. Gravimetric and volumetric power densities are approximately 0.1–0.4 kW/kg and 18–26 kW/l (displacement volume), respectively, at rated maximum power.

4.4.5. Electric-Vehicle Power Plants

4.4.5.1. *General Comments.* Most people do not realize that many early automobiles were electric vehicles. They were competitive with internal combustion engine powered vehicles at the beginning of the 20th century. However, as both technologies developed, it became clear that the internal combustion engine vehicles would have a lower cost, and development of this type accelerated while development of electric vehicles declined. Then, in 1990 the California Air Resources Board adopted a requirement that 10% of all new cars offered for sale in 2003 and beyond must be zero emission vehicles (ZEVs). This reflected renewed interest in advanced batteries and electric vehicle technology. While this rule has since been modified, the mandate stimulated a great deal of work on battery-powered vehicles, since they were the only near-commercial vehicle technology. In recent years, research on electric vehicles has declined significantly as battery technology has not progressed rapidly enough to provide adequate vehicles range. However, many of the advances in a wide range of vehicle technologies, such as aerodynamics, lightweight materials, energy storage, electric motors, and electronic

controls, will be useful for internal combustion engine, hybrid, and fuel cell vehicles.

4.4.5.2. *Principles of Operation.* An electric vehicle has a propulsion system that uses motors rather than a gasoline engine. Electrical energy stored on the vehicles, typically in batteries, is delivered to electric motors (via an electric controller) to turn the wheels. Generally, DC motors are more mature and will be used in low-cost and near-term electric vehicles, while AC motors are considered to have more potential benefits in terms of efficiency, reliability, and size.

Electric motors do not require a transmission system because their speeds and torque output are suitable for powering the wheels, although gears may be used to allow the motors to run at higher speed and thereby increase efficiency. Motors can be directly connected to individual wheels, potentially eliminating the need for a differential and improving handling and traction control. Electric motors have enough torque and can start from a stopped point while engines typically require gears to generate enough torque and need to idle at some low rpm, even under no load.

The control and power electronics are used to control the flow of power to the motors. Microprocessor-based control systems use a series of models that describe the driving situation, vehicle, and battery state to translate the driver's demands into the proper energy flow. Driver inputs can include steering, acceleration, and braking, while system control outputs can include motor torque and speed, gear ratio, regenerative braking, and battery charging.

Electric vehicles tend to be highly optimized, and significantly more efficient than one powered by an internal combustion engine. Advances to reduce the road load power (power to move a vehicle at a given speed and acceleration) include lighter weight, lower rolling resistance, and improved aerodynamics while the development of regenerative braking can reduce energy losses.

11.4.5.2. *System Issues.* A major area of research and development for electric vehicles is improvement of the energy-storage system: increasing the energy density and consequently the range between recharging, as well as decreasing the recharge time. The development of higher-capacity energy storage is a key challenge for developing vehicles that are convenient and acceptable to consumers. The ability of batteries to store only limited amounts of energy compared to liquid fuels is a major limitation on the electric vehicle. Battery development has been ongoing for many years. The US Advanced Battery Consortium (USABC) was founded in 1991, composed of the three major US auto manufacturers and the US Department of Energy. There was some progress in battery technology, but the research never led to large leaps in energy density. Other electricity sources, like fuel cells, have prospects to greatly improve the energy density and range by converting hydrogen and air directly to electricity.

Improving the electric-vehicle battery charging was another important area of research because of the typically long charging times. Convenience for the

consumer is of primary concern as drivers are used to refueling their vehicles in a matter of minutes, whereas batteries are best charged slowly at a low current and would take several hours. Inductive coupling methods have been developed for rapid charging at high currents.

11.4.5.3. *Environmental Benefits.* Electric vehicles have numerous benefits in large urban areas with poor air quality. The total emissions associated with operating electric vehicles depend on the details of electricity generation (i.e., the type of power plant, fuel, and plant efficiency); however, it is expected that there is a significant reduction in total emissions compared to conventional vehicles. In addition, one of the main benefits is that emissions are shifted both spatially and temporally so that none of the emissions occur from the tailpipe. The generation of photochemical smog and ground level ozone is very location and time dependent so that these shifts can greatly reduce the impact of transportation on urban air quality.

11.4.6. Hybrid Powered Vehicles

11.4.6.1. *Unique Characteristics and Benefits.* Hybrid vehicles are automobiles that have two distinct power sources that complement one another to power the vehicle. Hybrids are being developed and utilized because of the main benefit of increased vehicle efficiency as well as the indirect benefit of reduced pollutant emissions (CO_2, CO, NO_x, and VOC). There are various hybrid configurations, but the most common one consists of a SI or CI engine and electrical battery storage as the power sources. Other possible energy storage devices are flywheels and ultra-capacitors. These energy storage devices are described in more detail in the portable power section.

11.4.6.2. *Fundamentals of System Operation.* The configuration of the IC engine-battery hybrid-power source with respect to how mechanical power is supplied to the wheels can be *parallel* and *series* (Figure 11.11.) In the parallel configuration, the SI or CI engine (as described in Sections 11.4.3 and 11.4.4) converts the combustion of fuel into the rotation of the crankshaft that powers the transmission or generates electricity via a generator. Electricity supplied by the battery can power an electric motor that is also connected to the transmission; thus, the two power sources provide power to the wheels. In a series hybrid, there is only one energy path. The engine is connected only to the generator. The series hybrid electric car thus essentially functions as one with an on-board internal combustion engine-powered recharging station. In both designs, the motor/generator stores excess energy in the battery during braking/decelerating or when the power generated by the engine is greater than needed. The battery is then capable of providing the extra power to the transmission for start-up and acceleration.

11.4.6.3. *Thermal Efficiency and Fuel Efficiencies.* Engine thermal efficiency and vehicle fuel economy are increased in hybrid vehicles, as compared

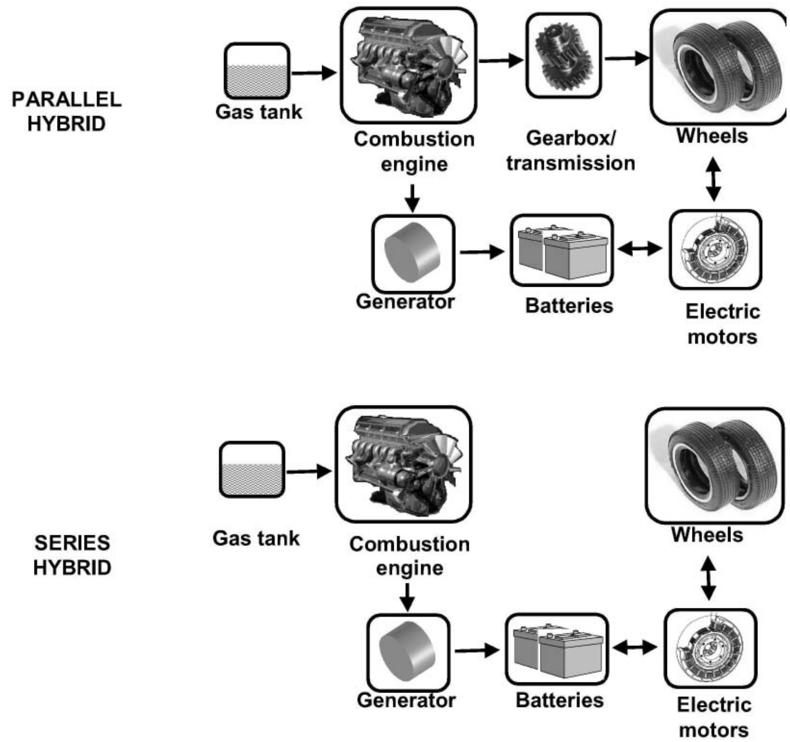

Figure 11.11 Schematic of parallel and series gasoline-battery hybrid vehicles.

with only gasoline-engine powered vehicles. These gains can be attributed to several factors:

- *Smaller engine size*. Engines can be sized to provide much less power than the maximum required by the car. The hybrid engine will be more efficient for several reasons. Part load efficiencies are typically higher than the efficiency at rated power and the range of power outputs will be much smaller than for a traditional engine. Also, several hybrid designs turn off the gasoline engine when idling.
- *Regenerative braking*. It permits recapturing some of the energy that would otherwise be lost as heat in the brakes by using the electric motors to act as generators and using that energy to charge the energy storage devices.
- *Advanced vehicle design*. Lightweight materials, reduced-rolling resistance, and improved aerodynamics improve fuel economy. The road-

load equation describes the mechanical power requirements (P_{road}) for a vehicle under certain driving conditions:

$$P_{road} = C_R M_v g V + \frac{1}{2}\rho_a C_D A_v V^3 \tag{11.19}$$

where C_R is the coefficient of rolling resistance; M_v is the mass of vehicle; g is the acceleration due to gravity; ρ is the air density; C_D is the drag coefficient; A_v is the frontal area of the vehicle; and V is the vehicle speed. Reductions in C_R, M_v, and C_D will reduce power requirements to power a vehicle at a given velocity. The first two factors increase engine efficiency while the third factor increases fuel usage efficiency for a given engine thermal efficiency. For example, even with a slightly heavier total vehicle weight and similar vehicle aerodynamics, the Honda Civic hybrid model claims a 40% gain in fuel economy over the standard Civic [from 35 mpg (6.75l/100km) to around 50 mpg (9.65l/100km)] because of the inclusion of a smaller, more efficient engine.

Examining a typical drive cycle can help to understand the efficiency benefits of the hybrid vehicle. Figure 11.12 represents a plot of energy requirements as a function of power generated for a typical urban drive cycle of a small automobile. The significant fraction of the energy use occurs at a power below 18 kW. Yet there are occasions that the vehicle demands a power output beyond 40 kW. The hybrid allows the combustion engine (or any primary power source) to be smaller (~ 20 kW), and the batteries (or secondary energy storage device) can provide power for these infrequent transients.

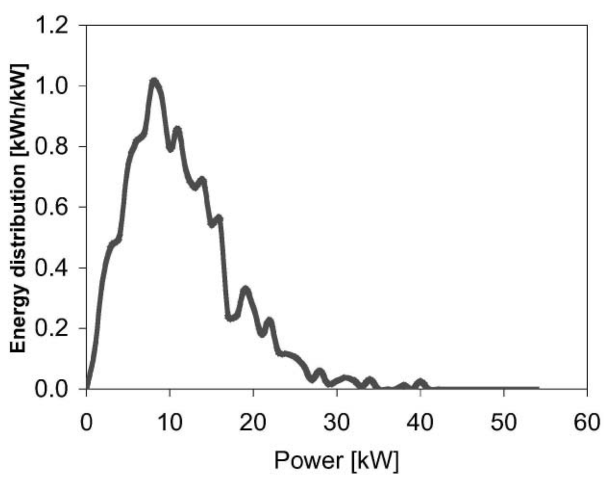

Figure 11.12. Typical driving-cycle power requirements.

11.4.6.4. *Emissions and Control.* Hybrid vehicles currently operate on four-stroke spark-ignition engines and have the same emissions characteristics and control processes as conventional vehicles. However, because of improved efficiency, the amount of fuel consumed and pollutants emitted will be reduced. The narrower range of engine operating speeds will also reduce emissions.

11.5 PORTABLE POWER

11.5.1. Background

Many different devices use portable power sources but the rapid growth in digital and wireless technologies is fueling the need for improvement and higher capacities. Cell phones, laptop computers, wireless organizers, and email devices are all drawing increasing amounts of power as they incorporate more powerful microprocessors, larger, full color screens, and wireless technologies to send and receive data almost anywhere. These high-tech devices, as well as other lower-tech devices, can draw as little as a few milliwatts in standby mode all the way up to 100 W. The most powerful devices can only operate at full power for a few hours before requiring an AC adapter or fully charged battery. Because of these short operating times and the growth of portable electronic devices, a great deal of research is being carried out to develop new power sources for this application, including advanced batteries and direct methanol fuel cells. Alternative energy and electricity storage devices are also discussed.

11.5.2. Batteries

Primary and secondary batteries make up the vast majority of energy storage devices used in portable power applications. They range from tiny batteries with capacities of 10 mWh to larger batteries with capacities of 25 kWh. The fundamental electrochemistry of batteries is described in more detail in Chapter 3.

Conventional primary batteries, such as alkaline Zn/MnO_2 batteries, are the most common and abundant. Other primary batteries include lithium batteries, which have approximately doubled gravimetric and volumetric energy density compared to the alkaline battery.

Secondary batteries, also called rechargeable batteries, can be reused over thousands of cycles. Conventional and advanced secondary batteries include lead-acid, Ni/Cd, Ni/MH, Li-ion, and zinc-air batteries. The lead-acid battery is the most widely used, lowest cost rechargeable system. It is most often used for automobile starting-lighting-ignition (SLI) systems. Nickel cadmium (Ni/Cd) batteries have higher energy density than lead-acid batteries. Nickel/metal hydride batteries (NiMH) are fairly common in a wide variety of applications including cell phones, laptop computers, cameras, and videocameras. The advanced Li-ion battery utilizes

lithium because it has the highest electrochemical potential and currently provides the highest energy density. The zinc-air battery is a hybrid power source essentially combining a battery and a fuel cell. Because it uses an air/oxygen cathode, the zinc can take up a much greater portion of the total volume of the cell, providing a very high energy density. The performance characteristics (gravimetric and volumetric energy density, cost) of secondary batteries are generally poorer than those of primary batteries because of the complex design challenges involved in making a battery that can be recharged over hundreds or thousands of cycles.

11.5.3. Environmental Aspects

Because Cd is toxic, Ni-Cd batteries have for the most part been replaced by NiMH batteries, despite the poorer charge retention of the NiMH type. In general, the use of secondary batteries reduces the environmental impact associated with battery disposal.

11.5.4. Other Energy Storage Devices

11.5.4.1. *Flywheels.* Flywheels can store mechanical energy in the form of rotating kinetic energy. The benefit of any mechanical energy storage device is that the conversion between electrical energy and kinetic/mechanical energy can be very high using generators and motors. A flywheel is a disc shaped mass rotating about an axis. The kinetic energy stored in a flywheel is given by the equation:

$$E = \frac{1}{2} I\omega^2 \tag{11.20}$$

where ω is the angular speed (rev/sec) and I is the moment of inertia, the resistance of a mass to angular motion. The further away from the axis the mass is distributed, the greater the moment of inertia and the greater energy storage is possible. In general, flywheels are shaped like bicycle tires with mass distributed around at a fixed distance from the axis. Energy is transferred to the disc by electric motors and extracted by running the motors as generators.

The advantages of flywheels compared to batteries are the very high round-trip efficiencies (electricity to kinetic to electricity), the potential for high power density, and a potentially long life. The disadvantages are the fairly low energy density and the hazard of uncontrolled release of energy upon failure.

11.5.4.2. *Compressed Air.* Large-scale systems exist where air is compressed and stored in underground caverns. Compression occurs when cheap, off-peak electricity is available, and electricity is generated during peak consumption periods by expanding the gas through a turbine-generator set. Some small systems may also be used as energy storage in vehicles or other applications.

Although small scale compressed air energy storage systems are not commercialized, there is some development going on as the secondary energy source for hybrid vehicles. The benefits of compressed air systems are high energy storage density and a potentially simple system with high efficiency. One disadvantage involves the heat that needs to be removed/added as the gas is compressed/expanded.

11.5.4.3. *Ultracapacitors.* Ultracapacitors (also called supercapacitors) can charge and discharge very rapidly, allowing very high-power operation for short times, or extended discharge times at low power. Ultracapacitors store energy electrochemically, although different types exist. Like simple fuel cells or batteries, they are composed of two electrodes and a separator/electrolyte. The electrodes are typically very high surface area porous carbon. Simple ultracapacitors store energy by charging the double layer. As charge is placed onto the electrode, ions migrate to the electrolyte/electrode interface, creating a double layer. In more complex ultracapacitors, some of the ions that enter the double layer are adsorbed on the surface of the electrode, and the charge may be transferred or merely intercalated into the electrode structure. Under these circumstances, the amount of energy/charge stored increases. The rate of charge and discharge may be reduced if charge transfer and ion intercalation reactions occur. Ultracapacitors store much less energy than batteries, but the energy can be released at significantly higher power. More details are given in Chapter 3.

11.6. TECHNO-ECONOMIC ASSESSMENTS: FUEL CELLS AND COMPETING TECHNOLOGIES

11.6.1. General Comments

This Section presents brief comparative assessments of fuel cells and the competing technologies discussed in the preceding Sections for the following applications:

- utility-scale power generation/cogeneration,
- small-scale remote and distributed power,
- transportation, and
- portable power.

Such comparisons can be rather challenging to make because many of the competitive technologies are in a significantly more mature state of development than fuel cells with well demonstrated value and wide-scale deployment. For these technologies, the operating parameters, system and environmental characteristics, and capital and operating costs are fairly well known. Fuel cells, as well as other alternative technologies, are in a rapid state of development, and much of the

information necessary for detailed comparisons is not well known. For example, only a few fuel cells are currently in use, including the alkaline fuel cells developed for the US space program, phosphoric-acid fuel cells commercialized by UTC-Fuel Cells, and a number of demonstration units and prototypes. One final important point is that the competing technologies for fuel cells will, in 5–50 years, also have advanced.

Each of the applications listed above has specific requirements. The following Sections present tables of projected and actual values of important characteristics. The difficulty in comparing vastly different technologies, some of which are well established while others have yet to be proven, should be taken into account when viewing these tables. There are many criteria for judging technologies, and a balance of engineering and economic characteristics will determine how a utility, company, or individual chooses a power source for its specific projects.

11.6.2. Power Generation/Cogeneration

The most important characteristics of a power generation technology are reliability, efficiency, service life, capital and operating costs, and environmental impact. Fuel cells are being considered for utility scale power generation because of high efficiency and ultra-low levels of emission of environmental pollutants, and minimal health hazards. Additional benefits include operation with hydrogen, which is a flexible fuel made from any number of sources, including carbon-free renewables. A comparison of some of the engineering and economic parameters for fuel cells and other power generating technologies is made in Table 11.2.

Major competition for fuel cells over the coming decades will be natural gas and gas turbines in combined-cycle power plants. Coal is a very low cost fuel in much of the world and will also be used widely. Advanced "clean coal" power plants are being developed around the integrated gasifier combined cycle (IGCC), or gas turbines. Both IGCC and gas-turbine combined-cycle power plants have high efficiencies (40–60%) and low levels of environmental pollutants, perhaps comparable to fuel cells. Most importantly, their capital costs will likely be significantly lower ($500 to $1000/kW). The reduction of pollutants like NO_x, SO_x, and particulates can increase the costs of these technologies, but the most expensive environmental regulation would be a constraint on carbon dioxide emissions, especially for coal.

Fuel-cell power plants for this application are in the infant state of development and commercialization. Thermal power plants have been developed and commercialized during the past hundred years and well over several hundred-billion dollars have been spent for their development. On the other hand fuel cells for these applications have been researched and developed to a much lower extent, with investments of a few billion dollars. Thus, there is a need for automation of techniques for the manufacture of components, sub systems, and auxiliaries to lower the cost of fuel cells by at least a factor of four.

TABLE 11.2
Techno-Economic Assessments of Fuel Cells vs. Competing Technologies for Power Generation/Cogeneration Applications

Energy-conversion system/fuel	Power level, MW	Thermal Efficiency, %	Lifetime, y	Environmental impact	Fraction of current US power generation, %	Capital Cost, $/kW	Electricity cost, ¢/kWh	Capacity factor
Fuel cells, PAFC	0.2–10	35–45	5–20	CO_2	0	1,500[a]	6–10[a]	Up to 95%
Fuel cells, MCFC/ gas-turbine hybrid	0.1–100	55–65	5–20	CO_2	0	1,000[a]	5–9[a]	Up to 95%
Fuel cell SOFC/ gas-turbine hybrid	0.1–100	55–65	5–20	CO_2, NO_x	0	1000[a]	5–9[a]	Up to 95%
Coal-steam cycle	10–1000	33–40	> 20	SO_X, CO_2, NO_X, PM	50	1300–2000	2–5	60–90%
Advanced coal technology, IGCC	10–1000	43–47	> 20	CO_2, NO_x	0	1500–2,000	6	75–90%
Gas turbine, NG	0.03–1000	30–40	> 20	CO_2, NO_x	10	500–800	3–5	Up to 95%
Combined cycle gas turbine, NG	50–1000	45–60	> 20	CO_2, NO_x	2	500–1000	2–4	Up to 95%
Microturbines	0.01–0.5	15–30	5–10[b]	CO_2, NO_x	0	800–1500	6–10	80–95%
Nuclear	500 –1400	32	> 20	Radioactive waste	20	1500–2500	1.5–5	70–90%
Hydroelectric	0.1–2000	65–90	> 40	Ecosystem changes, fish	13	1500–3500	1–4	40–50%
Wind turbines	0.1–10	20–50	~ 20	Visual, noise	0.01	1000–3000	4–6	20–40%
Geothermal	1–200	5–20[c]	> 20[c]	SO_x, CO_2	0.04	700–1500	5–8	Up to 95%
Solar	0.001-0.1	10–15	25	--	0.001	2000–4000	10–40	< 25%

[a] Projections
[b] Before overhauls/rebuilding
[c] Depends on geothermal resource

Energy technologies that do not produce carbon emissions include nuclear power and those based on renewable sources (e.g., hydroelectric, geothermal, solar, and wind power). Electricity production could shift towards these sources if carbon dioxide emissions are regulated. Fuel cells potentially have zero carbon emissions if hydrogen is made from electrolysis of water using electric energy derived from these sources, but the cheapest hydrogen for many decades will likely come from natural gas and coal. Therefore, the production of hydrogen will produce CO_2. Nuclear power plants have had significant problems with public perceptions for the difficulty of safety and nuclear waste disposal. However, a number of new reactor designs are being developed which could significantly lower cost and improve safety and reliability. If public perception is altered and more emphasis is placed on carbon-free energy sources, nuclear power could continue to provide a significant fraction of our electricity. Hydroelectric and geothermal power plants are limited by available resources, and most of the best sites have already been developed, limiting the extent of future development. Wind turbines are starting to become economically competitive with more traditional electricity sources and rapid development of wind farms is occurring. Some forecasts call for wind power to provide 3–5% of electricity in the USA by 2020.

The benefits of fuel cells for electricity generation are the very high efficiencies achievable with high temperature fuel cells (SOFC and MCFC), especially when coupled with gas turbines in a combined cycle configuration. These systems are able to achieve efficiencies anywhere from 50 to 75%. In addition, the emissions of NO_x, particulates, SO_x, and other pollutants will be zero or near zero. However, the CO_2 emissions of fuel cell systems will depend on how the hydrogen is produced. Coal based hydrogen production would still produce CO_2 although this technology, coupled with fuel cell power plants, could reduce carbon emissions due to increased efficiency. However, even with very optimistic cost projections, it will still be a challenge for fuel cells to reach capital costs parity with the fossil fuel combustion based systems. While a great deal of engineering development is currently going into lower cost materials and manufacturing techniques for fuel cells, it is unclear if cost targets necessary to compete with gas turbines are likely. In addition, the hydrogen fuel for these fuel cells will also be higher in cost than other fuels (coal, natural gas), because hydrogen will be produced from these fuels. One of the other main concerns about fuel cells is the lifetime. To date the projected goals are that the electrochemical stacks will last for 40,000 hours with minimal degradation in performance; after this period, the cell stacks may need replacement. However, if the costs for refurbishment for cell stacks can be considerably reduced by automation of techniques and mass production, these costs could be brought down to the levels of maintenance costs of thermal power plants. Further, in the case of the fuel cell power plants, the balance of plant sub-systems could have a lifetime of over 20 years, comparable to those of thermal power plants. Because of the scale-up limitations, lifetimes and capital costs, fuel cell power plants are also being considered for peak-power demands by electric utility, while the large conventional thermal power plants provide the base-load power. For such a case, even though the

capital and fuel costs of the fuel cell are relatively high for base-load power, they may not be excessive for peak power generation.

11.6.3. Small-Scale Remote and Distributed Power

Because remote and distributed power spans a wide range of engineering and economic requirements, it is difficult to define the most important factors. The goal of this Section is to address some of the possible factors that influence choices made for these applications. For small-scale remote and distributed applications, the important performance characteristics are similar to those for utility-scale electricity generation. In general, economic characteristics such as capital cost and operation, maintenance, and fuel costs and engineering characteristics such as efficiency, reliability, and capacity are key considerations for choosing power sources for these applications.

In general, higher unit costs are often tolerated in these applications because there are no acceptable lower cost alternatives. Providing grid electricity for remote terrestrial applications is generally very costly (involving the building of transmission lines), so that significantly higher capital and operating costs for stand-alone power generation systems are often tolerated. For remote military, marine and space applications, costs can be much higher and very specific engineering requirements can determine which technologies are chosen. By placing generating capacity near the end user, distributed generation often allows the utility to add additional generating capacity to the grid without upgrading substations and transmission lines. In addition, distributed generation also offers the possibility of high reliability standby power in the event of outages, peak power shaving, and cogeneration.

For many remote power applications, gasoline and diesel engine generators are used because they are proven technologies with low capital and fuel costs. In locations that have access to natural gas, propane, or landfill gas, microturbines are at an early stage of commercialization and appear to offer many similar characteristics to reciprocating engines, while also providing the possibility for cogeneration hot water.

Fuel cells are currently used for remote power applications on the Space Shuttle because of the benefits of using hydrogen fuel, which has a high gravimetric energy density. In addition, the product water is used as a potable water source for astronauts. But even for space applications, the energy source will depend upon the requirements of the mission and the resources available. For example, the International Space Station (ISS), when completed, will rely mainly on about 240 kW of solar modules and battery storage. For long duration space probes which do not receive enough solar radiation, NASA has used thermoelectric generators with the radioactive decay of nuclear materials as the heat source.

As with large-scale utility generation, the advantages of fuel cells are high efficiency, near-zero emissions of criteria pollutants, and minimal noise pollution. In remote applications where the difficulties are in generating any power at all,

these reasons may be less compelling. In remote power applications, it may be impractical or uneconomical to provide fuel. In these cases, renewable energy sources, such as solar, wind, or small hydro often make sense. Which energy source is utilized will depend upon what resources are available in that location. In general, acceptable solar resources may be more widely distributed, but capital costs are higher than for wind power. The cost of electricity will depend strongly on the capacity factor and quality of the resource. For remote and off-grid homes and buildings or other remote applications, photovoltaic solar panel systems often make sense, especially coupled with battery energy storage, and perhaps an engine generator backup.

Depending upon the availability of fuel in these locations, fuel cells for remote applications may make sense. The use of waste heat in addition to electricity may also be beneficial for specific purposes. Propane or natural gas reformers can produce hydrogen for use in fuel cells. These reformers add to the capital cost of the fuel cell systems. The benefits of fuel cell systems include lower noise than internal combustion engines, significantly higher efficiency, and lower emissions. These smaller fuel cell systems could be phosphoric acid (PAFC) or proton exchange membrane fuel cells (PEMFC).

The benefits associated with distributed generation often permit higher costs and lower efficiency than for central station power. Premium power customers demand high quality and reliable electricity for critical loads such as in hospitals, banks, apartment buildings, factories, and computer server farms. The increase in digital technologies is also increasing the need for high quality electricity. Peak power is also becoming important as utilities begin to charge real-time prices for electricity. Technologies including microturbines and diesel engines are suitable for providing backup and peak power. Fuel cells are a possible alternative to these more conventional technologies.

11.6.4. Transportation

The most important performance characteristics of power sources for automotive applications are cost, energy conversion efficiency (%), power density (W/l), specific power (W/kg), energy density (kWh/l), and specific energy (Wh/kg), in addition to lifetime and impact on environment and health. Enthusiasm and interest for the development of fuel-cell powered vehicles was stimulated in the late 1970s with the program *Fuel Cells for Electric Vehicles*. However, with rapidly decreasing oil prices in the 1980s, the incentives for alternative energy programs decreased. The California zero-emission vehicle (ZEV) mandate has renewed interest in fuel-cell powered vehicles. At about the same time, several battery programs with the lead acid battery and the advanced nickel/metal hydride and lithium ion batteries as power sources for electric vehicles were stimulated. In this Section, a techno-economic assessment is made of these power sources for electric vehicles, in comparison with the conventional spark ignition and diesel engine powered vehicles, as well as with the battery powered and hybrid systems (IC

TABLE 11.3
Techno-Economic Assessments of Fuel Cells vs. Competing Technologies for the Transportation Applications

Energy conversion system / fuel	Power Level, kW	Thermal efficiency, %	Specific power, kW/kg	Power density, kW/l	Vehicle range, km	Environmental impact	Capital cost, $/kW
Fuel Cells, PEMFC / H_2, methanol or gasoline onboard fuel-processor	10–300	40–45	400–1000	600–2000	350–500	CO_2	100[a]
Fuel Cells, PEMFC direct H_2	10–300	50–55	400–1000	600–2000	200–300	CO_2	100[a]
SI engine / gasoline	10–300	15–25	> 1000	> 1000	600	NO_x,CO_2 HC, CO	20–50
Diesel engine	10–200	30–35	> 1000	> 1000	800	PM, CO_2 NO_x	20–50
CIDI / battery hybrid	50–100	45	> 1000	> 1000	> 800	PM, CO_2 NO_x	50–80
ICE-battery hybrid / gasoline	10–100	40–50	~ 1000	~ 1000	> 800	NO_x, HC, CO	50–80[a]
Battery / lead acid, Ni-MH	10–100	65	100–400	250–750	100–300	CO_2	> 100

[a] projected costs
Note: Capital costs for fuel cell and battery power plants are projected

engine/battery), the latter incorporated into Toyota and Honda hybrid electric vehicles (see Table 11.3). Fuel-cell powered vehicles are much less mature compared to conventional vehicles, while hybrid vehicles have significant experience over several years and are maturing rapidly.

Current and advanced hybrid are the most compelling vehicle technology with respect to increasing fuel economy of vehicles, reducing emissions, and meeting cost goals. The US Partnership for a New Generation of Vehicles (PNGV) Program (1993 to 2001) selected three advanced hybrid vehicle technologies: the diesel engine (CIDI)/battery, the fuel-cell battery, and the gas turbine/battery. The main competition for fuel-cells in a hybrid vehicle is from the diesel engine, which provides high efficiency and fairly low costs. Table 11.3 shows that PEMFC power plants for automobiles and PAFC power plants for fleet vehicles may be able to compete with ICE or diesel engine powered vehicles with respect to performance characteristics. However, the major challenge is in meeting the fuel cell cost targets of less than $50/kW. At the present time, fuel cell costs are off by a factor of about 100. In addition, the cost of hydrogen fuel will also be significantly higher than either gasoline or diesel fuels. If onboard reforming is to be utilized, the added capital cost of the reformer will also contribute significantly to overall cost. Cost is again the major consideration and the prospects for the dramatic cost reductions necessary to be competitive with internal combustion engines appear unlikely in the near term. The recommended methods for cost reduction are the same as those of power generation/cogeneration applications (see Section 11.6.2).

At the present time, hydrogen, stored as a compressed gas, appears to be the most feasible storage technology. The best cylinders made of composite materials for pressures up to 400 atm, yield a hydrogen content of about 6 wt%. This will amount to between 10–20% of the energy content in gasoline. Thus, the driving range of the vehicle will be limited. However, the higher efficiency of fuel will increase the driving range. Improving hydrogen storage and developing the infrastructure for producing, distributing, storing, and dispensing hydrogen to vehicles will be quite expensive. The challenges may be greater than those associated with reducing particulate and sulfur emissions from diesel engines and developing a higher energy-density battery. A major R&D effort has been proposed by the present USA administration to advance the technologies for hydrogen storage, transmission, and distribution for the transportation application.

CO_2 emissions are an important consideration in the future, and therefore, emissions from transportation need to be addressed because it is such a large contributor. While efficiency improvements can reduce emissions, both electricity and hydrogen can be made from carbon-free sources and greatly reduce carbon emissions from automobiles.

11.6.5. Portable Power

For portable power applications, the competitors for fuel cell power sources are secondary batteries—Ni/Cd, NiMH, and lithium ion batteries (Table 11.4). Because

TABLE 11.4
Techno-Economic Assessments of Fuel Cells vs. Competing Technologies for Portable Power Applications

Portable-power system and fuel	Grav. Energy density (Wh/kg)	Vol. energy density (Wh/L)	Power density (W/kg)	Capital cost ($/kWh)
DMFC	> 1000	700–1000	100–200	10–50[a,b]
Lead-acid battery	20–50	50–100	150–300	70
NiCd battery	40–60	75–150	150–200	300
NiMH battery	60–100	100–250	200–300	300–500
Li-ion battery	100–160	200–300	200–400	200–700
Alkaline battery (primary)	100–200	300–450	200–400	< 50
Flywheel	50–400	200	200–400	200–500[a]
Ultracapacitor	10	10	500–1000	~ 100[a]

[a] projected costs
[b] $/kW

of the toxic nature of cadmium the NiMH batteries are fast replacing the Ni/Cd batteries for various applications. Also, since 1997, the lithium ion battery has made impressive headway into these markets, the main reasons being its higher specific energy and energy density and its lower self-discharge rate relative to the NiMH battery. Another advantage is the potential of 3 V, whereas the operating potentials for NiMH batteries and fuel cells are 1.1 and 0.7 V, respectively. The number of Li ion cells will therefore be less than in an NiMH battery or fuel cell of the same voltage. Again, the high cost of fuel cells is a hurdle that needs to be overcome, but the advantageous characteristics of fuel cells, such as using higher energy density fuel (compared to batteries), will allow them to be competitive with batteries for specific portable applications such as cell phones, laptop computers, wheel chairs, golf carts, etc. For these applications, the required power levels will range from a few watts to a few kilowatts.

Other energy storage technologies such as flywheels and ultracapacitors do not have high energy density and may not be suitable for many portable applications. But some specialized applications can be found where their specific benefits may be useful, especially since they can charge and discharge at very high power.

11.6.6. Conclusions

Fuel cells still have a long and challenging road ahead before they can achieve significant usage in the applications described in this chapter. The major barrier is the high capital cost of fuel-cell systems. A great deal of research and development is underway to make engineering improvements in order to bring down this cost.

Automation of techniques for manufacture and mass production are vital to realize this goal.

The development of advanced technologies for utility scale electric power generation is an important goal because of the potential to increase thermal efficiency of the power plant and greatly reduce the emission of environmental pollutants and CO_2. Fuel cells offer the possibility of achieving these goals, along with several other advanced combined cycle systems operating with natural gas and coal. The main challenges for fuel cells are to demonstrate reliability and reduce capital costs. The cost reductions that are necessary to compete economically with the lowest cost technologies available today are unlikely, but there will be growing niche applications as the costs are lowered, and environmental benefits are considered or environmental regulations will be strengthened.

The fuel cell application with the greatest amount of interest is transportation, but it also appears to be the most difficult in the near term. A number of barriers must be overcome before commercial fuel cell vehicles can be at competitive prices and are embraced by consumers. The development of advanced internal combustion engines coupled with hybrid vehicle technology can significantly reduce the environmental impact of transportation energy use and thus reduce the incentives for developing fuel cell vehicles.

It appears that fuel cells will be commercialized first for portable power applications. In part, this is due to the high cost of portable energy (batteries) compared to the cost of fuels like gasoline, methanol, or even hydrogen. Also, in terms of performance, fuel cells appear to be able to meet or exceed the advanced battery systems. Although from a total energy perspective, the use of fuel cells for portable applications will not be a significant fraction of our energy use, it will be an important first step in the growth of fuel cells in a range of applications that will appear throughout the modern energy intensive world.

The presumption that fuel cells are an advanced energy technology that will revolutionize the world cannot be discounted. However, it is unlikely that this will occur in the next decade or so. Too many challenges exist, both from within fuel cell research, development, and engineering as well as from among competing technologies. The benefits of fuel cells are, in large, partly due to their efficiency, few moving parts, low levels of environmental pollutants, and negligible noise pollution; on the contrary the costs tend to be significantly higher. In general, this pattern is not uncommon. Environmental safeguards tend to benefit everyone while leading to higher costs. How and why people make decisions about their energy choices are important and have important policy implications. Environmental and social benefits of fuel cells or any other technology need to be mandated, regulated, or in some way encouraged for promotion of fuel cells to enter the energy sector.

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PROBLEMS

1. List 5 differences between diesel engines and SI engines and their implications on their use for specific applications.
2. Explain the differences between engine thermal efficiency and automobile fuel economy.
3. Assuming all other parameters to be constant, how would the power to overcome aerodynamic resistance and rolling resistance change between a speed of 55 mph and 75 mph?
4. What is the difference between the net power output of a thermal cycle and the power output of a turbine?
5. Make a graph of how Carnot efficiency changes with temperature (from 0–2000 °C), and compare it with a graph of how the theoretical fuel cell efficiency (based upon the Nernst equation) changes with temperature.
6. Describe three factors that limit the efficiency of internal combustion engines (automotive and stationary).
7. How would the drive train of a fuel cell hybrid differ from an internal-combustion-engine hybrid?
8. If Carnot efficiencies improve with temperature, what limits the highest temperatures at which power plant technologies can operate?
9. Describe the environmental impacts of each of the energy technologies described in this chapter.